Probing Little Higgs at LHC

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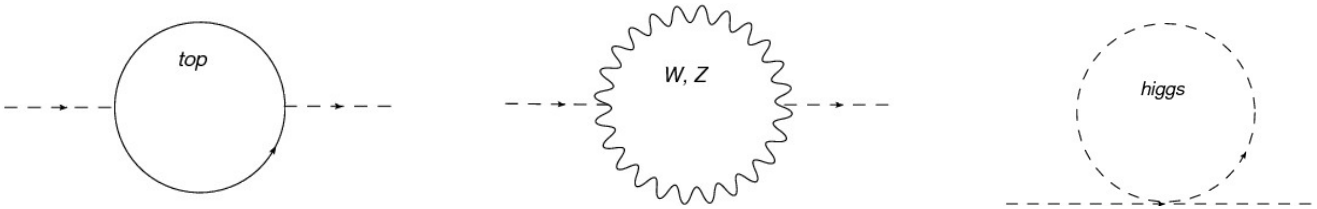
< LHC Physics meeting >

Outline

1. Motivation
2. Little Higgs approach
3. Various little Higgs models

Motivation

- Due to quantum corrections, the Higgs mass is quadratically sensitive to the cutoff scale: $\sim \Lambda^2$ ($\rightarrow$ naturalness problem?)



$$
\begin{aligned}
m_h^2 &= m_{H^0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2 + \frac{1}{16\pi^2} \lambda^2 \Lambda^2 \\
(200\ \mathrm{GeV})^2 &= m_{H^0}^2 + \left[-(2\ \mathrm{TeV})^2 + (700\ \mathrm{GeV})^2 + (500\ \mathrm{GeV})^2 \right] \left(\frac{\Lambda}{10\ \mathrm{TeV}} \right)^2 \\
&\Rightarrow \quad \Lambda \sim 1\ \mathrm{TeV} \qquad \rightarrow \quad \text{Fine-Tuning Issue}
\end{aligned}
$$

- Note that cutoff Λ for non-renormalizable operators such as $|H^\dagger D_\mu H|^2/\Lambda^2$ should be greater than about 5 TeV.

Little Higgs approach

- As an alternative solution to the naturalness problem (and the fine-tuning issue), little Higgs models (LHM) has been recently introduced.
  (Arkani-Hamed, Cohen, and Georgi 2001)
- LHMs adopts the early idea that Higgs can be considered as a Nambu Goldstone boson from global symmetry breaking at some higher scale $\Lambda \sim 4\pi f$.
  (Dimopoulos, Preskill 1982; Georgi, Kaplan 1984; Banks 1984)
- Higgs acquires a mass radiatively through symmetry breaking at the EW scale v, by collective breaking.
- Consequently, quadratic divergences absent at one-loop level $\Rightarrow$ cancellation among same spin states!

Introduction

Various little Higgs models

Model	Global Group	Gauge Group	EW-scale scalars	TeV-scale scalars
Minimal Moose	$SU(3)^8/SU(3)^4$	$SU(3)\times SU(2)\times U(1)$	h_1, h_2, ϕ, σ	(none)
Minimal Moose with $SU(2)_C$	$SO(5)^8/SO(5)^4$	$SO(5)\times SU(2)\times U(1)$	h_1, h_2	$\phi^r, \sigma^\pm, \sigma^r$
Moose with T-parity	$SO(5)^{10}/SO(5)^5$	$(SU(2)\times U(1))^3$	h_1, h_2	$h_{3,4,5}, \phi^r_{1,2,3}, \sigma_{1,2,3,4,5}, \eta_{1,2,3}$
Littlest Higgs	$SU(5)/SO(5)$	$(SU(2)\times U(1))^2$	h	ϕ
$SU(6)/Sp(6)$ model	$SU(6)/Sp(6)$	$(SU(2)\times U(1))^2$	h_1, h_2	σ
Littlest Higgs with $SU(2)_C$)	$SO(9)/SO(5)\times SO(4)$	$SU(2)^3\times U(1)$	h	ϕ, ϕ^r, η
Littlest Higgs with T-parity	$SU(5)/SO(5)$	$(SU(2)\times U(1))^2$	h	ϕ
$SU(3)$ simple group	$SU(3)^2\times U(1)/SU(2)^2\times U(1)$	$SU(3)\times U(1)$	h, η	(none)
$SU(4)$ simple group	$SU(4)^4\times U(1)/SU(3)^4\times U(1)$	$SU(4)\times U(1)$	h_1, h_2, η_1, η_2	$\sigma_1, \sigma_2, \sigma_3$
SU(9)/SU(8) simple group	$SU(9)/SU(8)$	$SU(3)\times U(1)$	h_1, h_2	σ_1, σ_2

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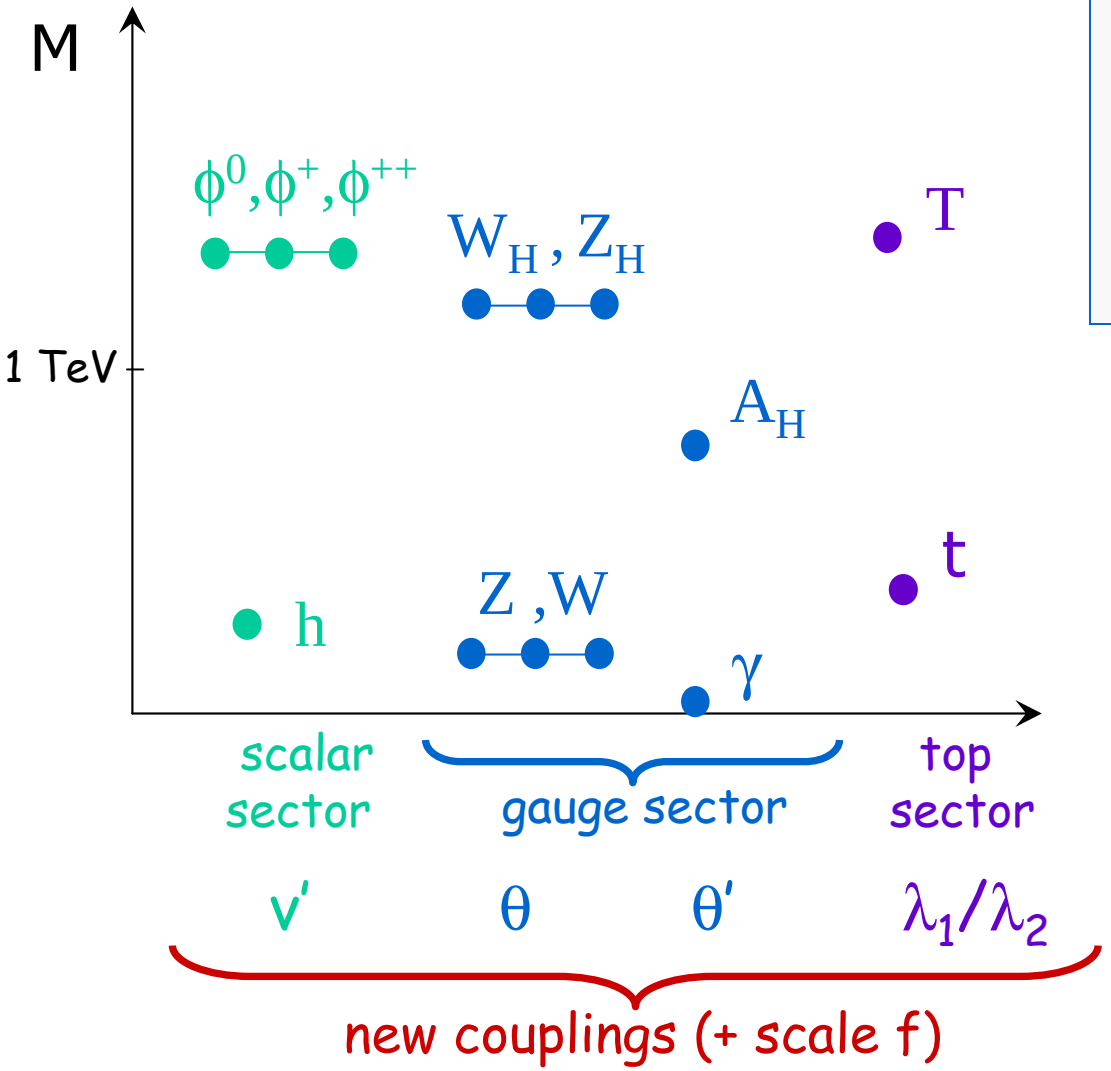
LITTLE HIGGS SEARCHES AT LHC

on behalf of ATLAS Collaboration

presented by: Jose E. Garcia *(IFIC-Valencia)*

Particle Spectrum



Littlest Higgs model

SU(5) → SO(5)

Gauge sector → $[SU_2 \otimes U_1]^2$

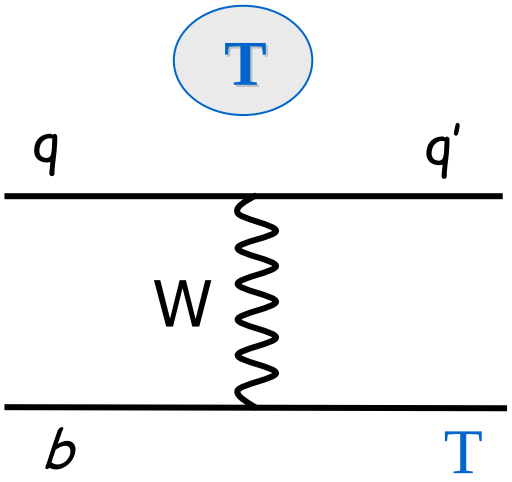
SM Higgs

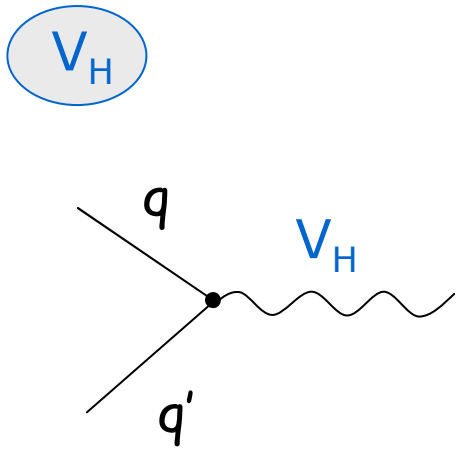
Arkani-Hamed et al., JHEP 207 (2002) 34

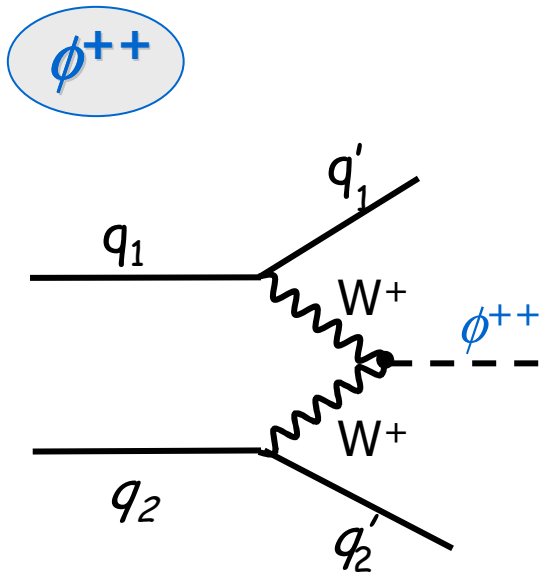
Phenomenology

- *Han et al., Phys. Rev. D67 (2003) 95004*
- *Burdman et al., hep-ph/0212228*

Strategies at LHC







Wb fusion

$\sigma \sim (\lambda_1)^2$

$\lambda_1 / \lambda_2 \sim 1$ suppressed by *b-quark* PDF.

$T \rightarrow bW, tZ, th$

$q\bar{q}$ annihilation

$\sigma \sim (\cot\theta)^2$

Wide range in *cot* θ possible.

$Z_H \rightarrow e^+e^-$ & $W_H \rightarrow \ell\, \nu$

$V_H \rightarrow V\, h$ (V is Z or W)

VBF mechanism

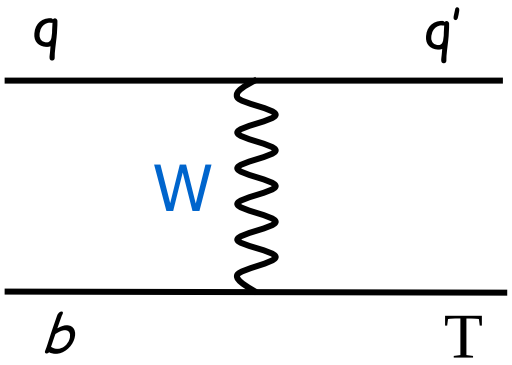
$\sigma \sim (v')^2$

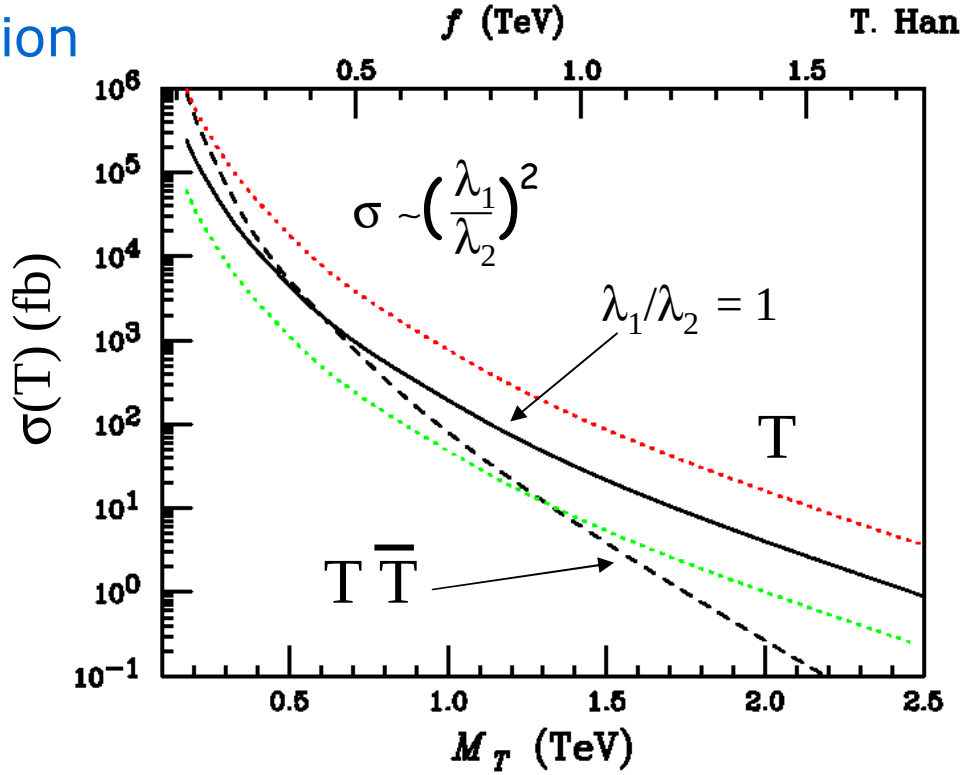
v' should be small

$\phi^{++} \rightarrow W^+W^+$

heavy top T

- Production mechanism = Wb fusion





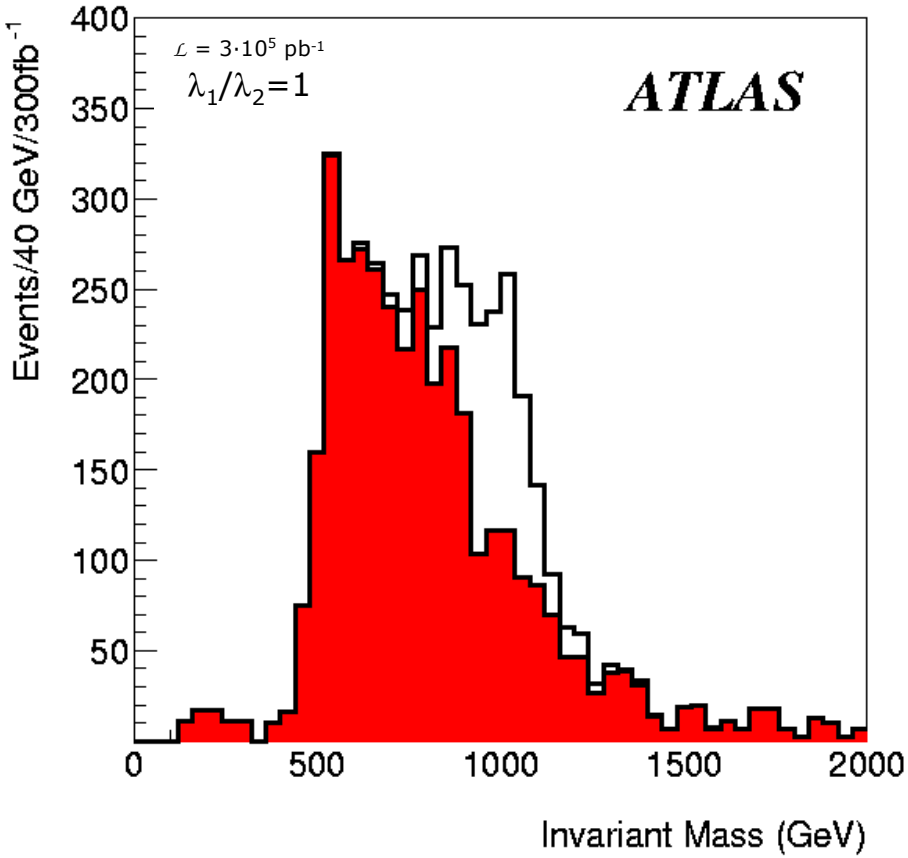
BR
- $T \rightarrow bW$ 50 %
- $T \rightarrow tZ$ 25 %
- $T \rightarrow th$ 25 %

λ_1 , λ_2 Yukawa couplings of T and t

$$\frac{\Gamma}{M} \approx \frac{1}{16\pi} \approx 2\ \%$$

$T \rightarrow Wb$

$T \rightarrow Wb \rightarrow$ b-jet + lepton + $\not{E}_T$



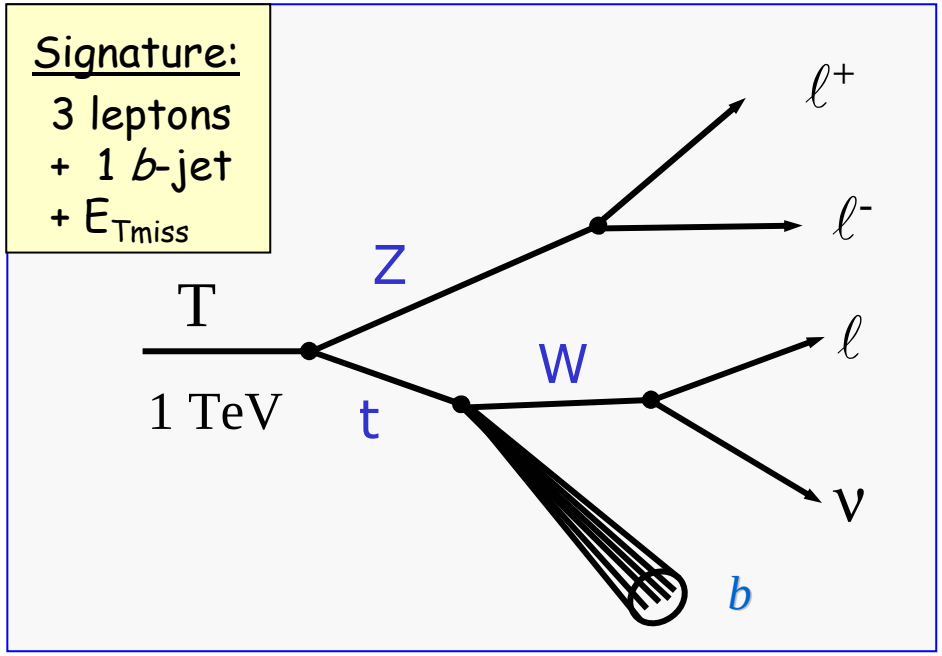
Cuts:
- p_T(jet) > 200 GeV
- p_T(lepton) > 100 GeV
- E_T > 100 GeV

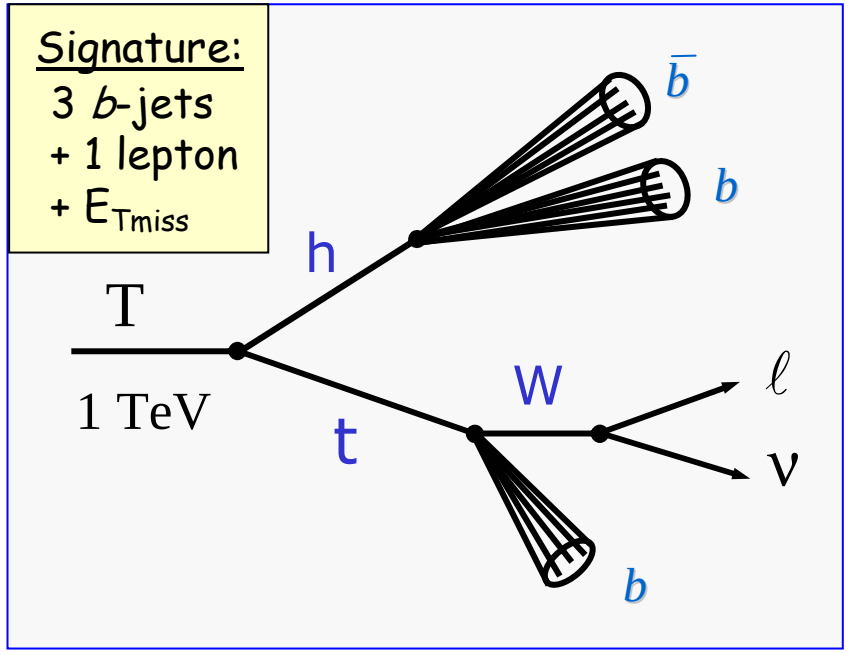
1 b-tag required

Backgrounds: $\bar{t}t$, t, $W\bar{b}b$

Signal with 5σ for M_T < 2000 GeV

$T \to Zt$ and $T \to ht$





BKG tbZ, tZ,WZ

clear peak but poor statistics

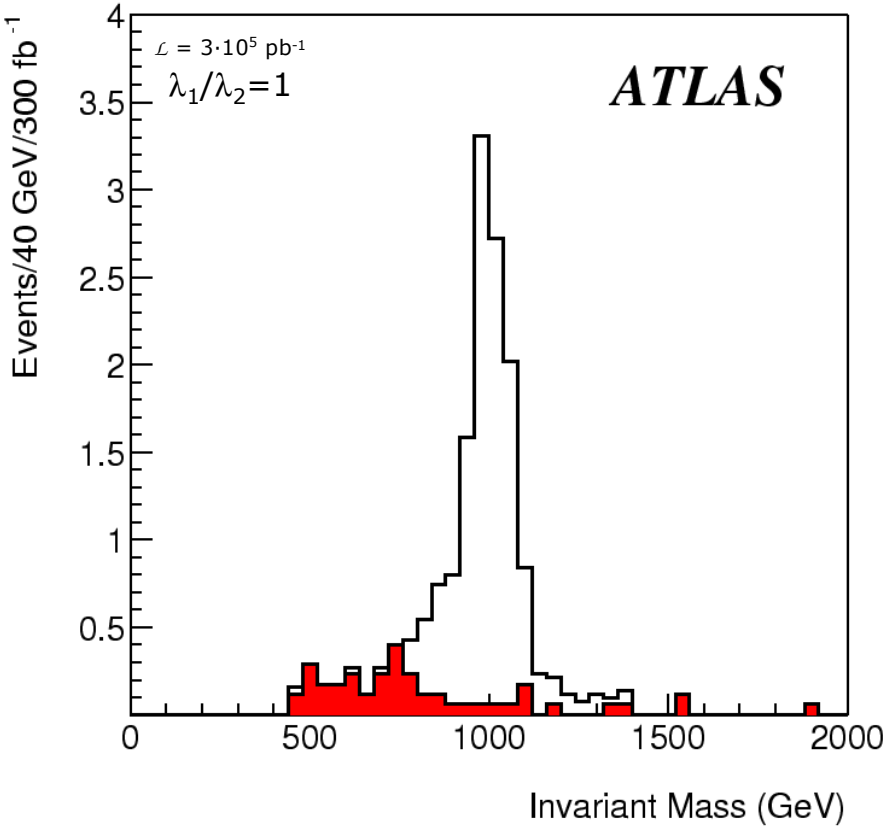
BKG $t\bar{t}$, $Wb\bar{b}$

Not distinguishable peak

$T \rightarrow Zt$ signal

M_T= 1 TeV

$T \rightarrow tZ \rightarrow$ 3 leptons + b-jet + $\not{E}_T$



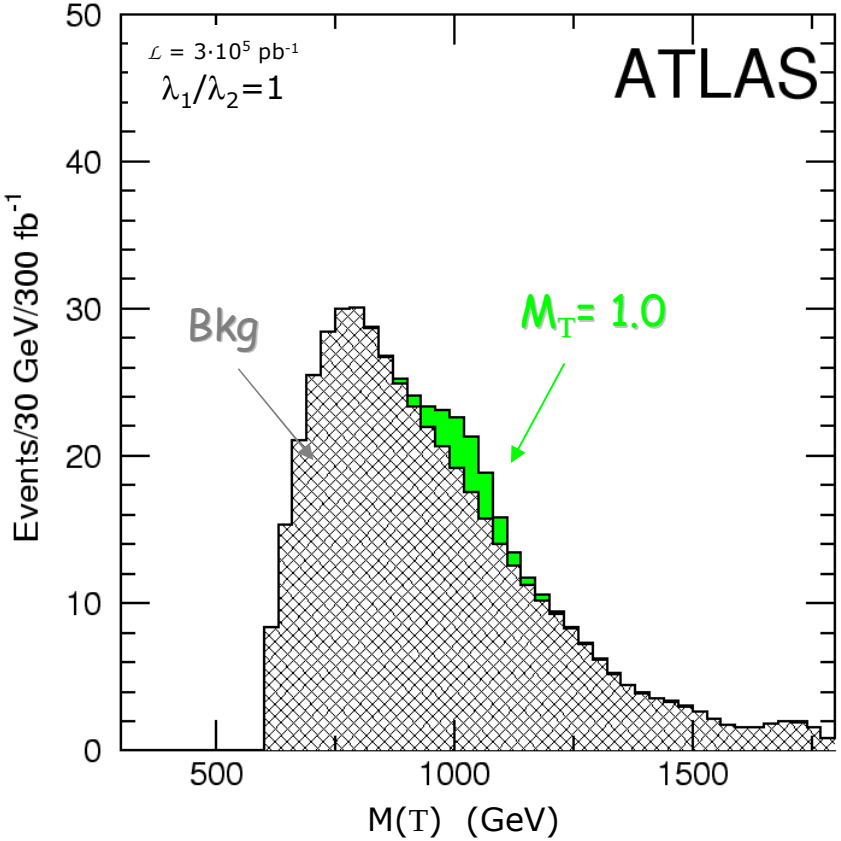
Cuts:
- *3 isolated leptons*
  (2 of them with $M_{\ell^+\ell^-} = M_Z$)
- 1 b -jet
- $\not{E}_T$ > 100 GeV

Signal with 5σ for M_T < 1050 GeV

$T \rightarrow ht$ signal

M_T= 1 TeV

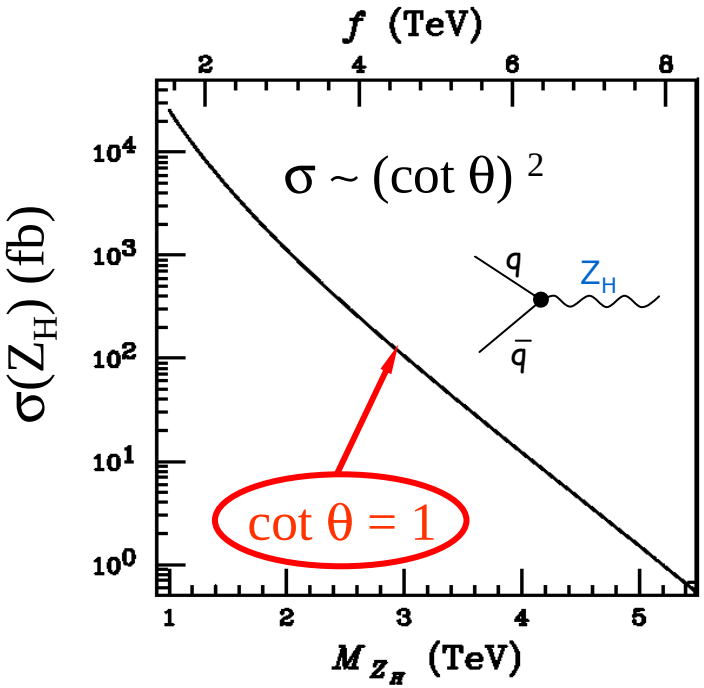
$T \rightarrow ht \rightarrow$ 3 b-jets + lepton + $\not{E}_T$

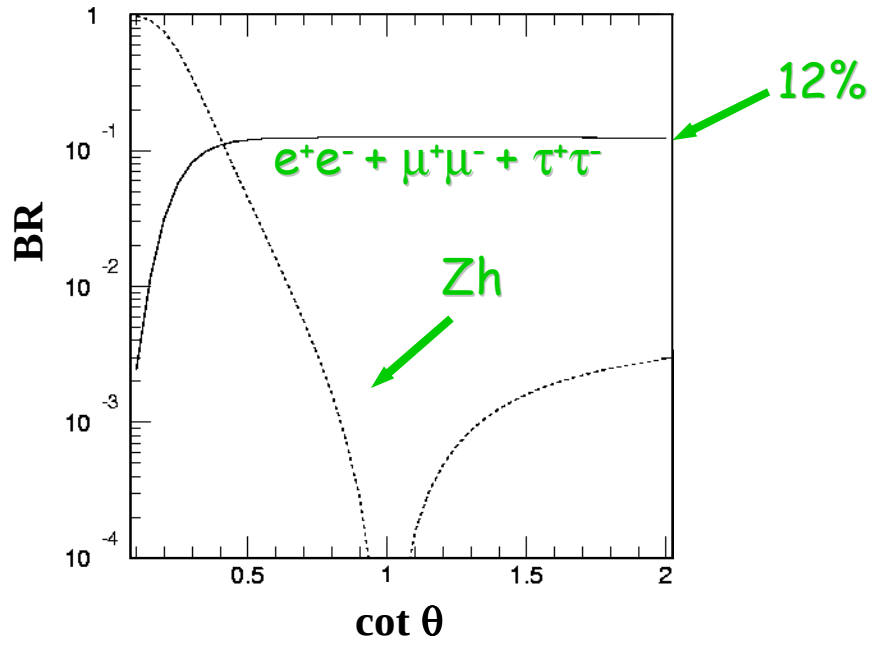


Cuts:
- p_T(3-jets) > 130 GeV
- p_T(lepton) > 100 GeV
- 110 < M_h < 130 GeV

At least 1 b-tag

Gauge Boson Z_H





Once a mass is given, the only free parameter in the model is, θ.

$$\Gamma(\ell\bar{\ell}) \sim (\cot\theta)^2$$
$$\Gamma(Zh) \sim (\cot 2\theta)^2$$

Search for Z_H

$M(Z_H)$ = 2 TeV $\mathcal{L} = 3 \cdot 10^5$ pb^{-1}

$q\bar{q} \longrightarrow Z_H \longrightarrow e^+e^-$

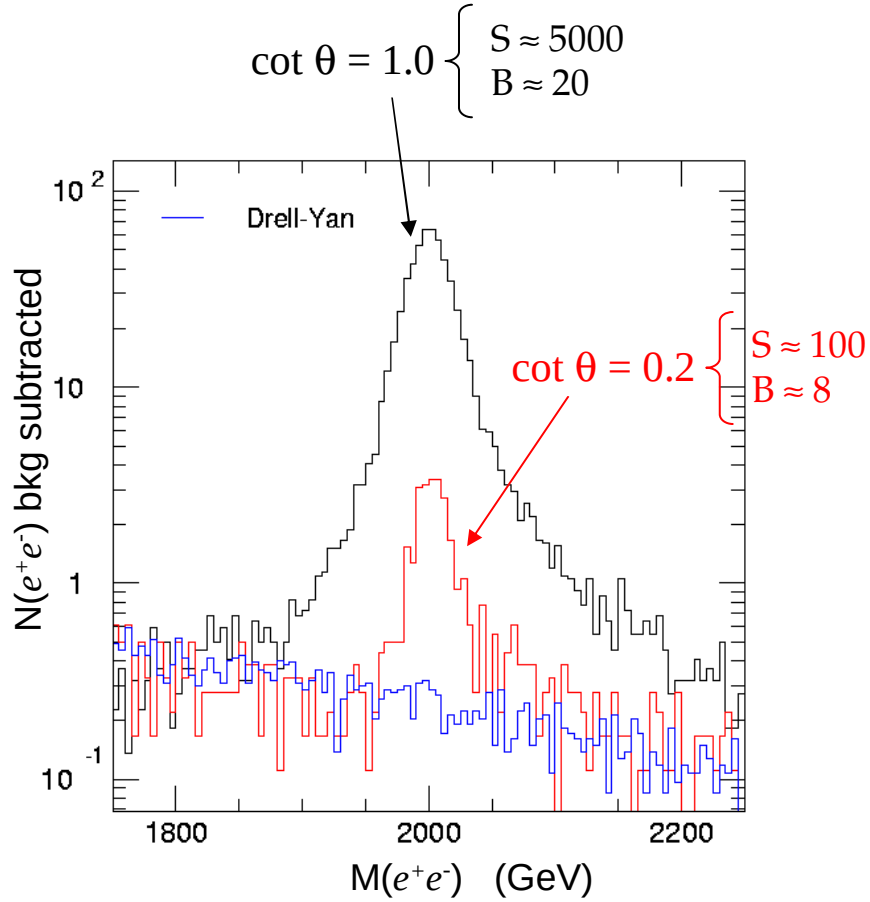
slight improvement is reached using also $\mu^+\mu^-$

Selection cuts:

- 2 isolated electrons with $p_T > 20$ GeV and $|\eta| < 2.5$
- minimum invariant mass equal to 800 GeV

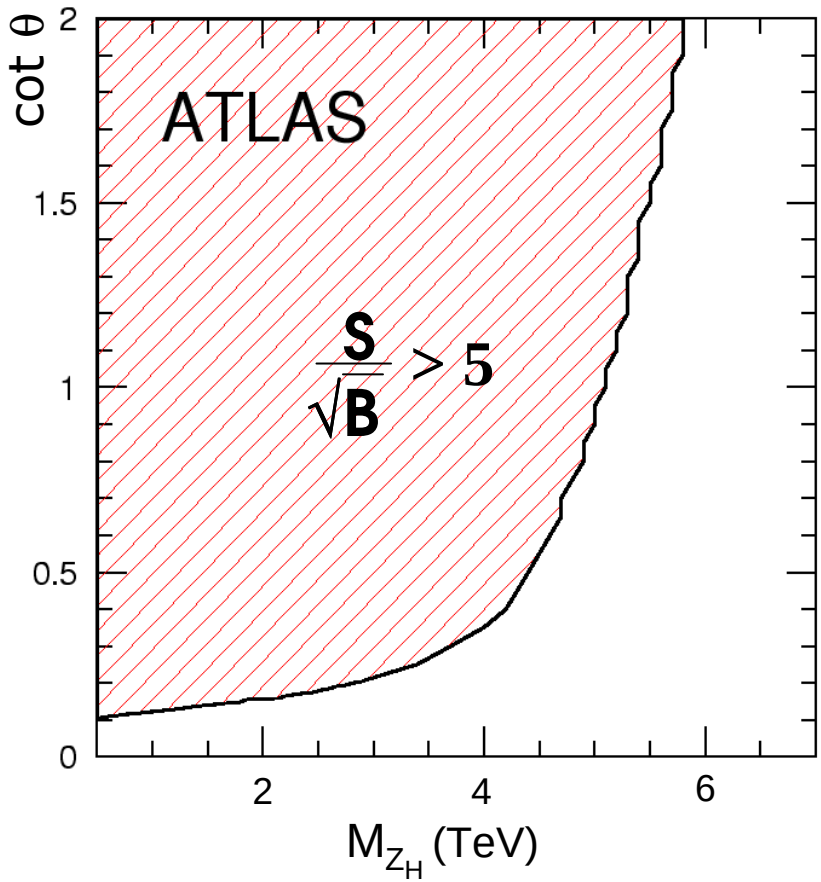
Background:

Drell-Yan ($q\bar{q} \rightarrow Z/\gamma \rightarrow e^+e^-$)



Discovery region for Z_H

$\mathcal{L} = 3 \cdot 10^5$ pb ^{1}



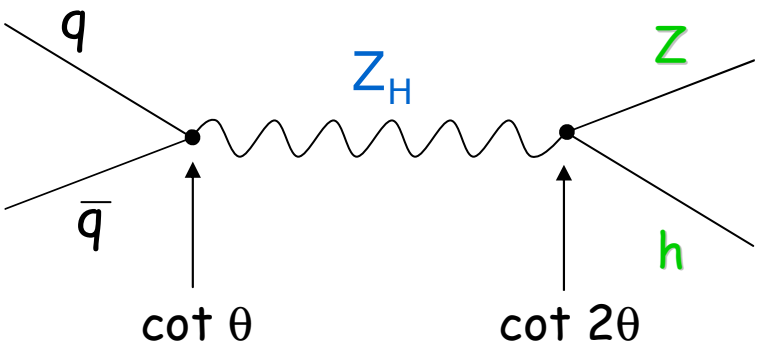
- $\sigma(Z_H)$ decreases as M increases
- $\sigma(Z_H) \sim (\cot\theta)^2$

  $BR(Z_H \longrightarrow e^+e^-)$ drops for $\cot\theta \rightarrow 0$

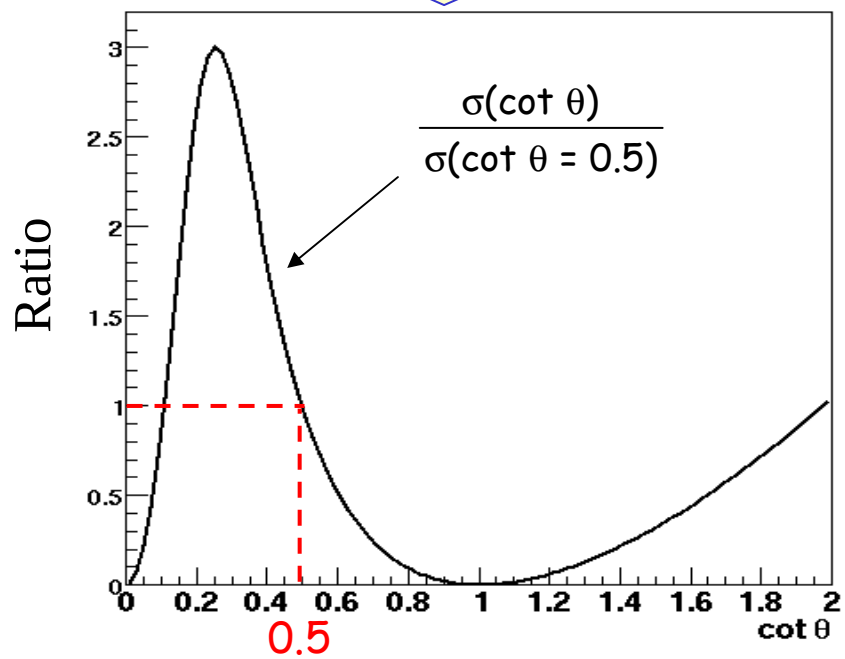
- If Z_H is found, $\cot\theta$ can be extracted from $\sigma(Z_H)$ and $\Gamma(Z_H)$

$$\frac{\Gamma}{M} = [\ 3.4\,(\cot\theta)^2 + 0.071\,(\cot 2\theta)^2]\ \%$$

$Z_H \rightarrow Zh$



$\sigma \sim (\cot\theta \cot 2\theta)^2$



m_h = 120 GeV

BR(h ⟶ bb) = 66 %

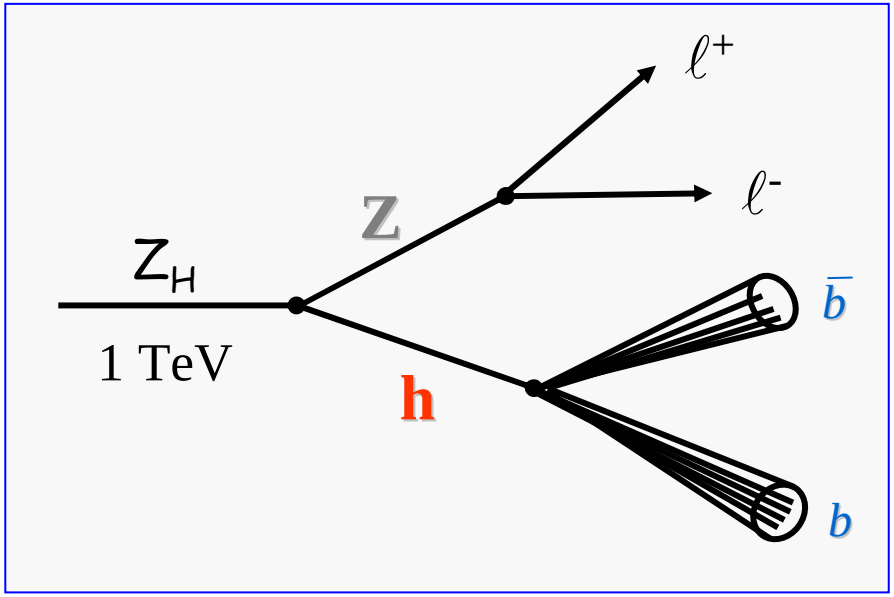
BR(h ⟶ γγ) = 0.2 %

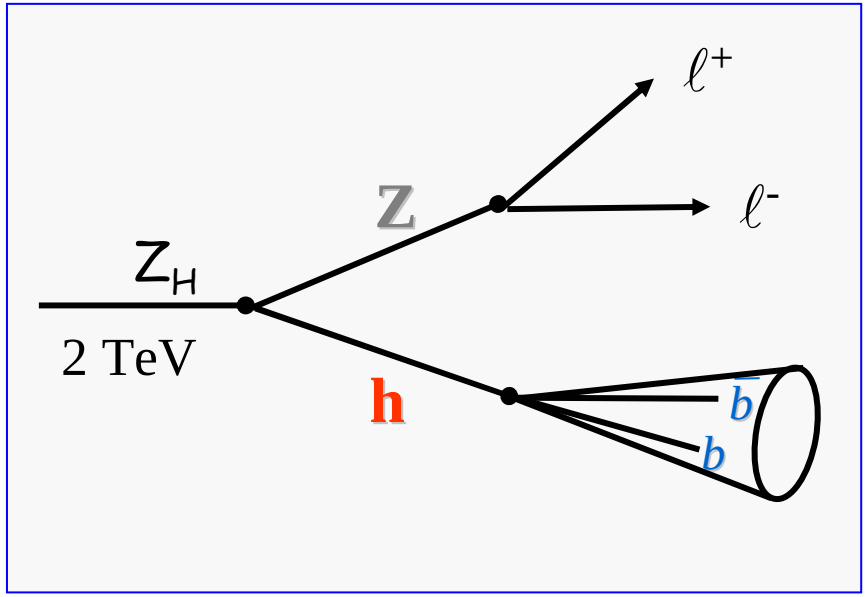
m_h = 200 GeV

BR(h ⟶ W^+W^-) = 74 %

BR(h ⟶ ZZ) = 26 %

$Z_H \to Zh$ with $h \to b\bar{b}$



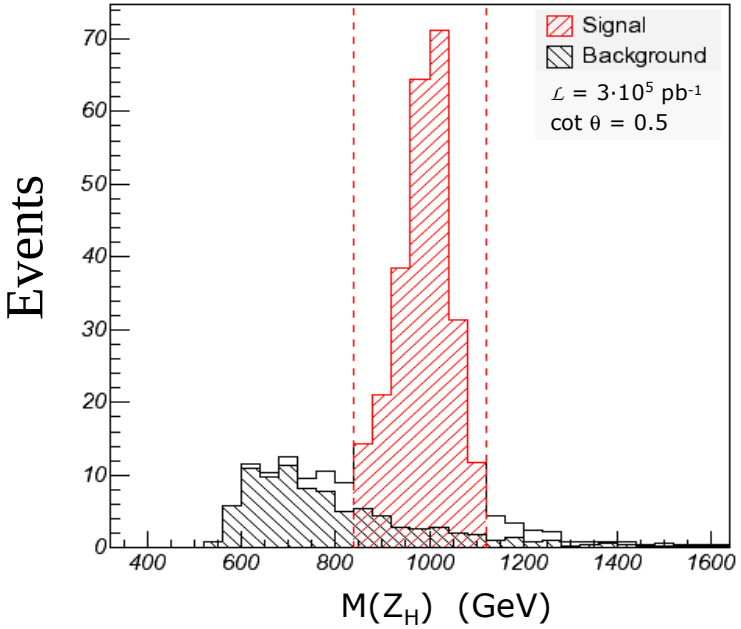


Cuts	Cuts
$\lvert\eta\rvert$ < 2.5 (jets and leptons)	$\lvert\eta\rvert$ < 2.5 (jets and leptons)
$P_T(Z)$ > 250 GeV	$P_T(Z)$ > 500 GeV
$P_T(h)$ > 250 GeV	$P_T(h)$ > 500 GeV
b-tagging	b-tagging

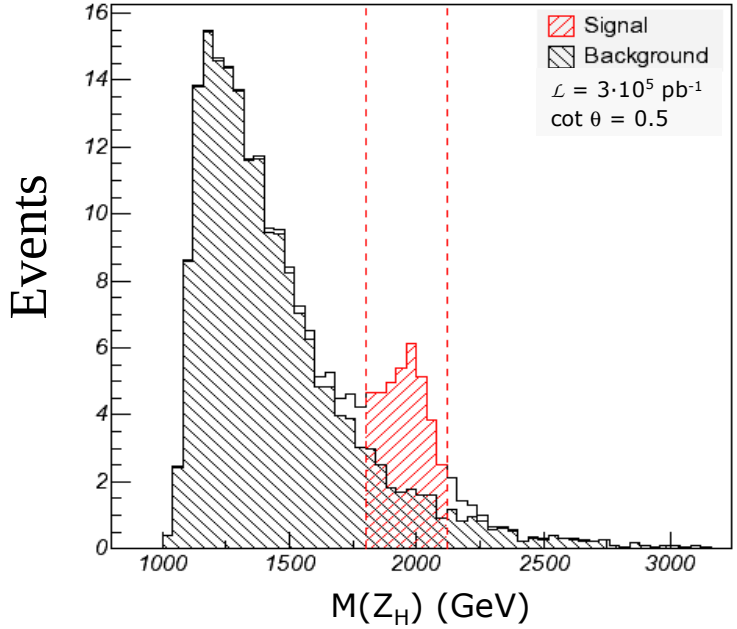
Background: Z + jets

$Z_H \rightarrow Zh$ signal

M_{Z_H} = 1 TeV



M_{Z_H} = 2 TeV



b-tag: ε_b = 50%, R_u = 100

Inside mass window:

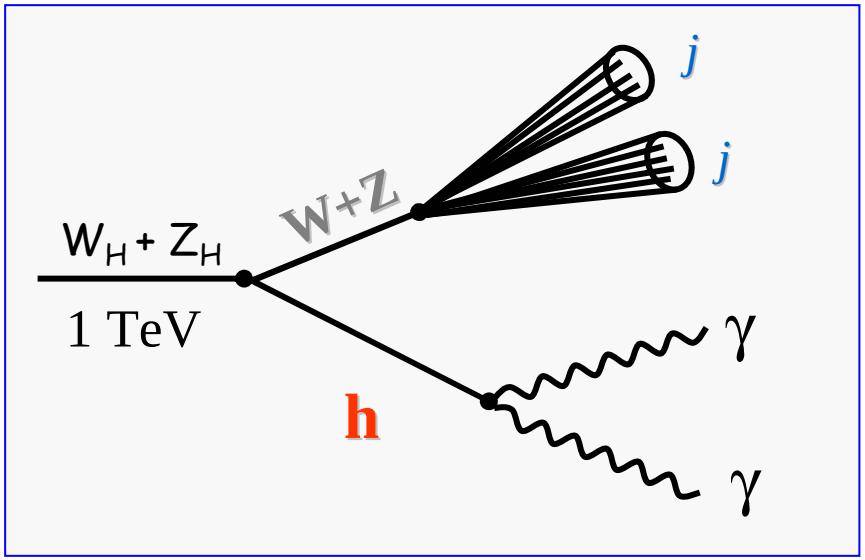
$$\left.\begin{array}{l} S = 195 \\ B = 16 \end{array}\right\} \quad \frac{S}{\sqrt{B}} = 50$$

b-tag: ε_b = 40%, R_u = 100

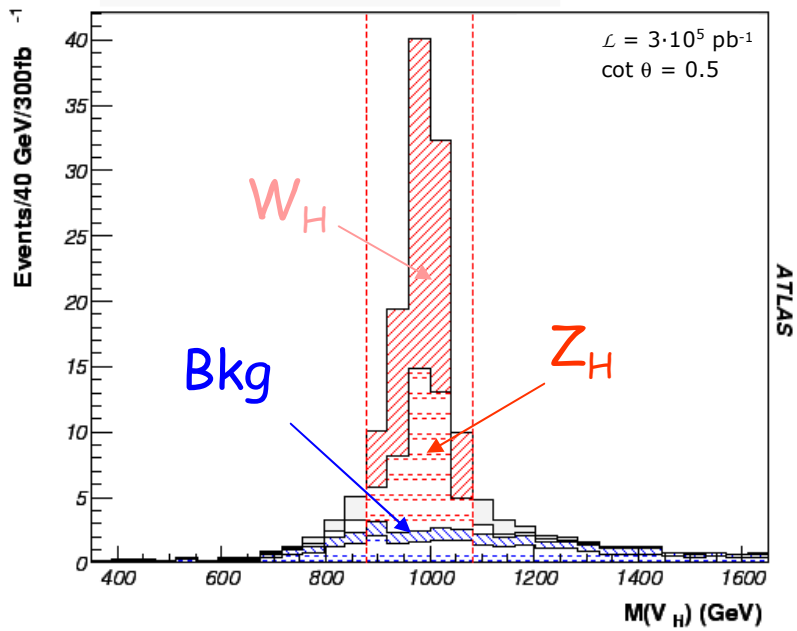
Inside mass window:

$$\left.\begin{array}{l} S = 15 \\ B = 8 \end{array}\right\} \quad \frac{S}{\sqrt{B}} = 5$$

$W_H / Z_H \rightarrow W/Z\ h$ with $h \rightarrow \gamma\gamma$



$M_{Z_H} = M_{W_H} = 1$ TeV



Cuts

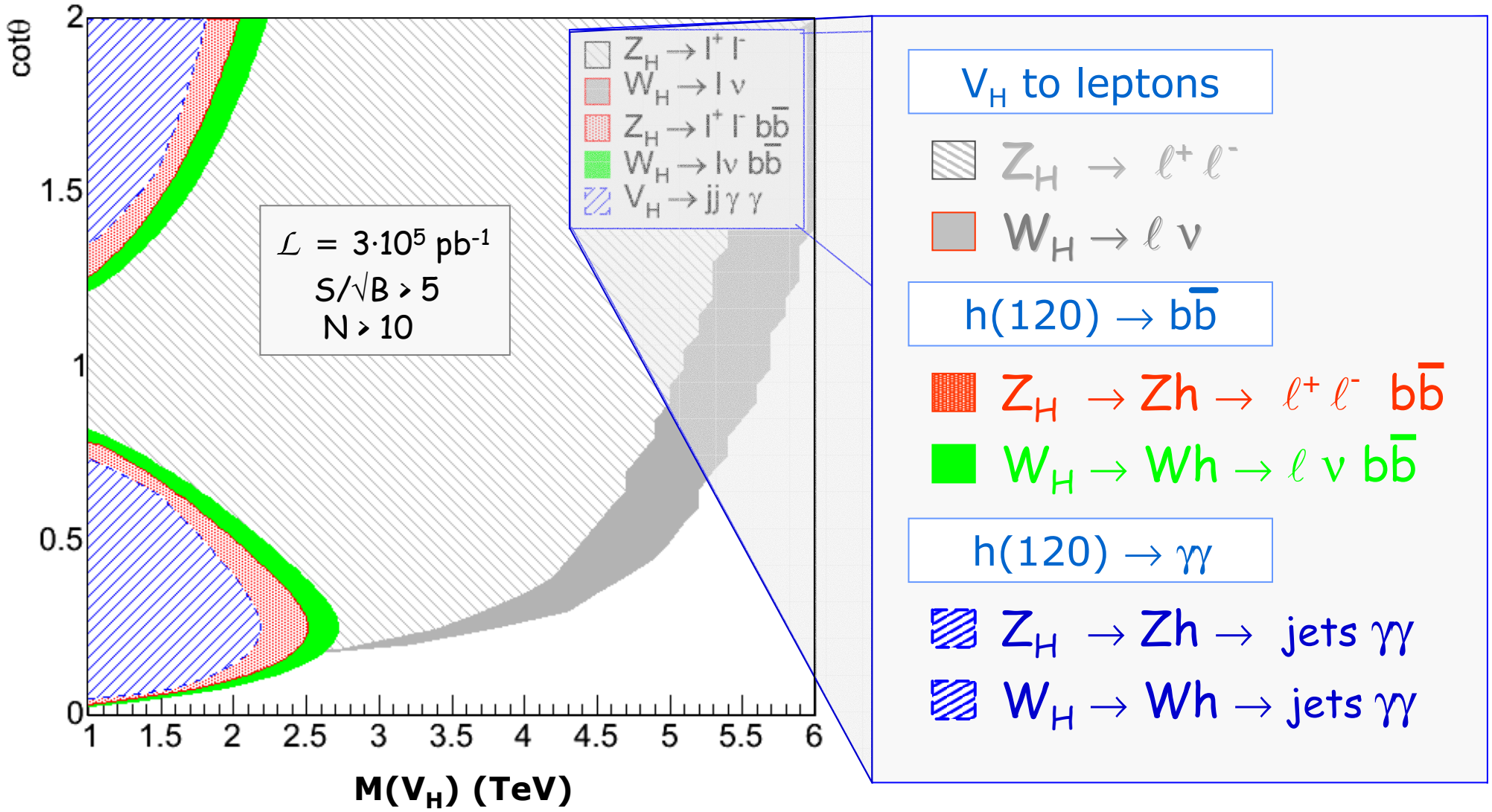
$|\eta(\gamma)| < 2.5$
$P_T(\gamma) > 25$ GeV
$P_T(h) > 400$ GeV
γ-tagging, $\varepsilon(\gamma) = 80\%$

$S(W_H \rightarrow Wh) = 64$
$S(Z_H \rightarrow Zh) = 33$
} 97

B(h inclusive) = 8
B($\gamma\gamma$ inclusive) = 5
} 13

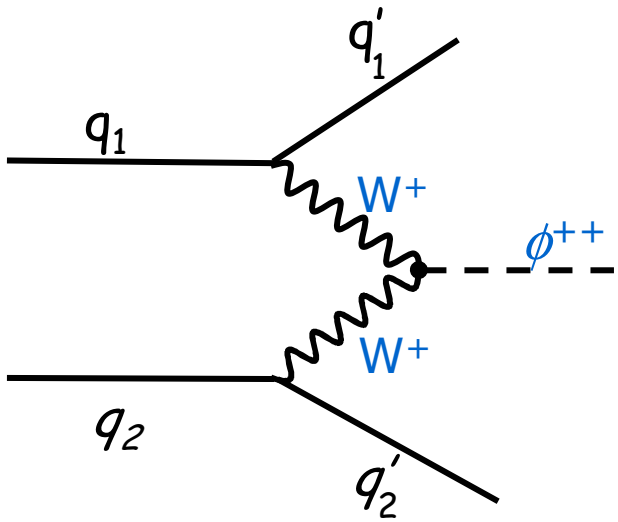
$$\frac{S}{\sqrt{B}} = 27$$

Discovery region for V_H



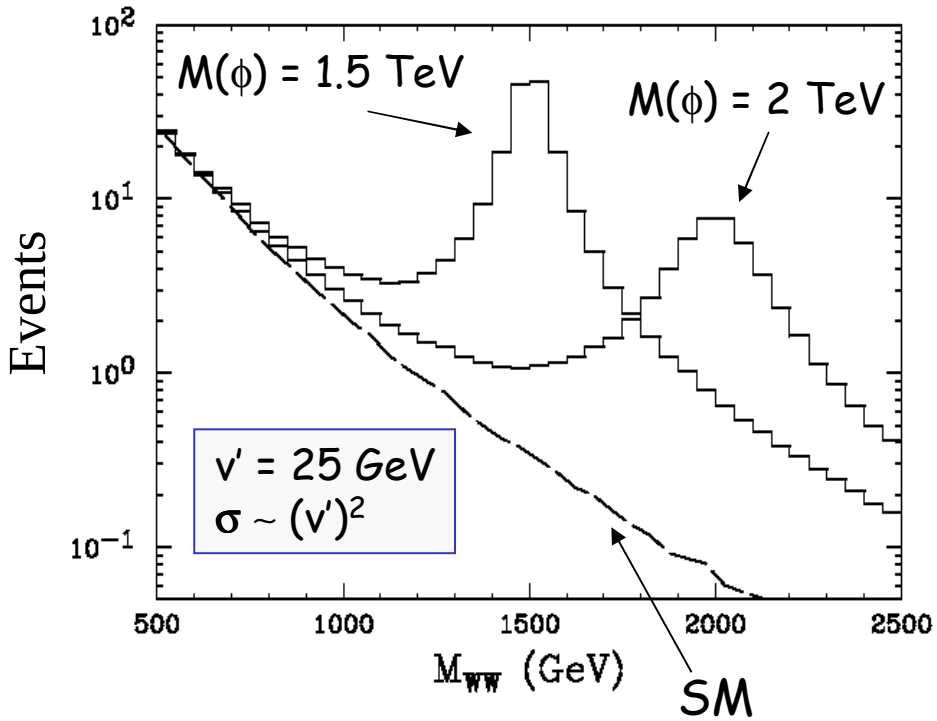
New Higgs ϕ^{++}

- Production: VBF mechanism
(vector boson fusion)



$\mathcal{L} = 3 \cdot 10^5$ pb ^{1}

$W^+W^+ \rightarrow \phi^{++} \rightarrow W^+W^+$



Decay: $\phi^{++} \rightarrow W^+W^+$

Decay of ϕ^{++} to leptons is suppressed in this model

$\phi^{++} \rightarrow W^+W^+$

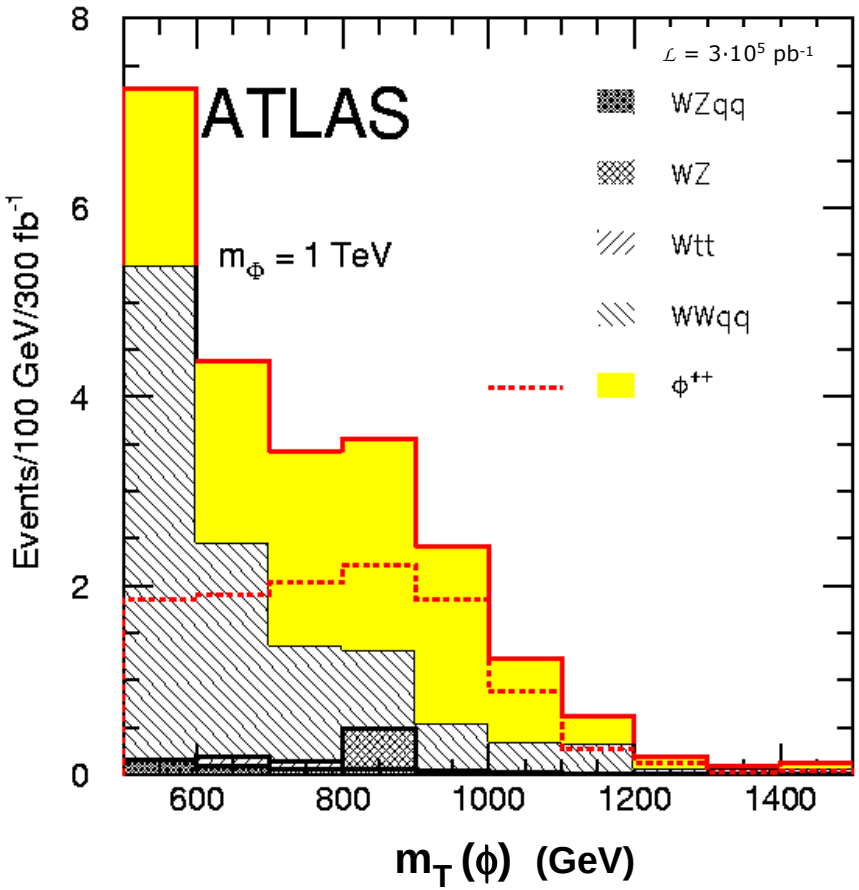
$\phi^{++} \rightarrow W^+W^+ \rightarrow \ell^+\ell^+\nu\nu$

Bkg: WWqq, WZ
WZqq, $Wt\bar{t}$

Main cuts:

- 2 forward jets (E > 100 GeV)
- 2 leptons (charge +)
- P_T(lepton 1) > 150 GeV
- P_T(lepton 2) > 20 GeV
- $\not{E}_T$ > 50 GeV

- m_T > 500 GeV



$$m_T = (E(\ell_1) + E(\ell_2) + |\vec{\not{p}}_T|)^2 + (\vec{p}(\ell_1) + \vec{p}(\ell_2) + \vec{\not{p}}_T)^2$$

Outlook and Summary

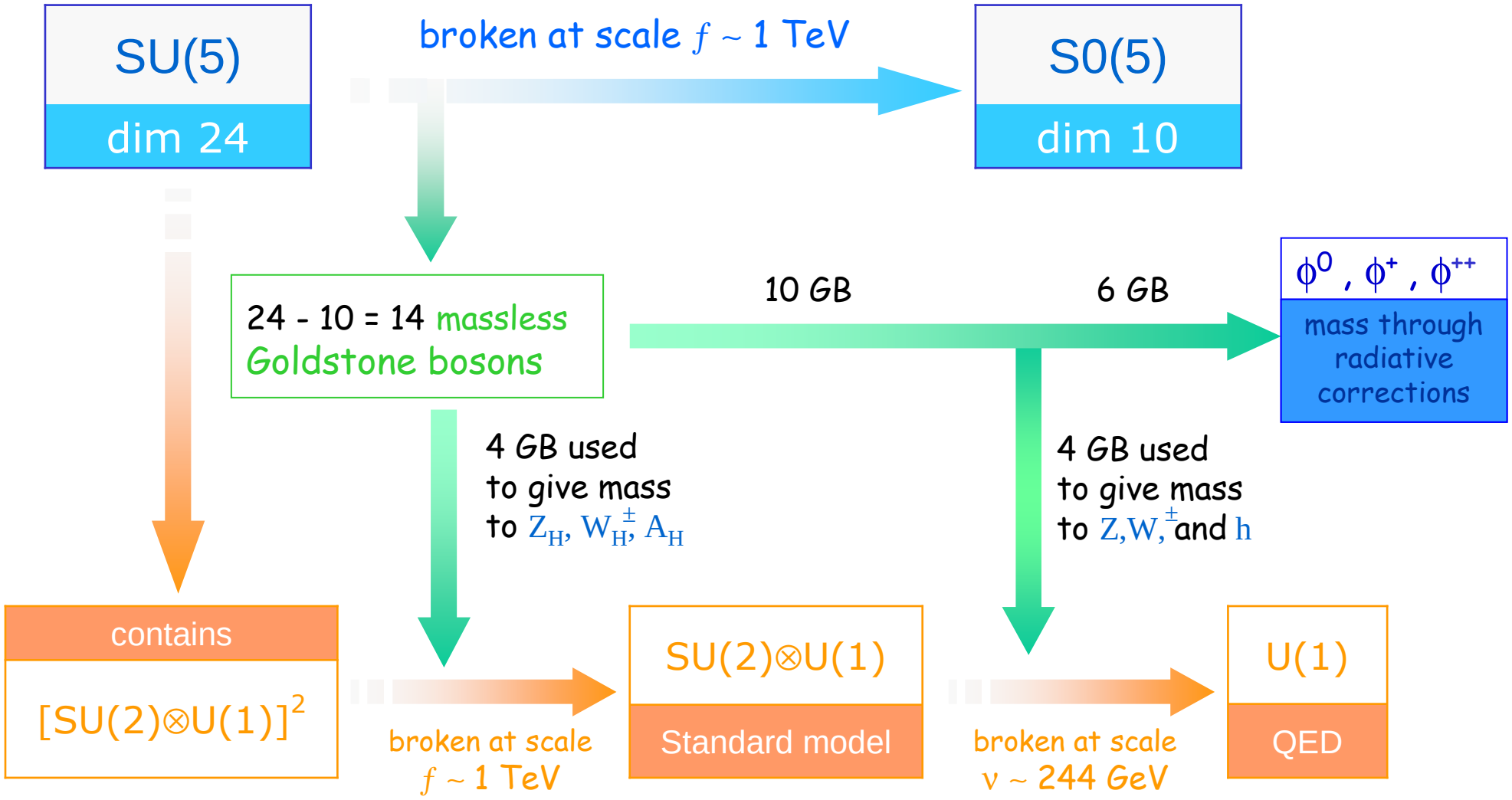
- Searches for the new particles predicted by Littlest Higgs model at LHC have been performed. Heavy Top and new Gauge boson sector are observable over a large range of parameter.
- "Toy" model used for the study severely constrained by electro-weak measurements
- Little Higgs idea is realized in several different models: *SU(5)/SO(5),SU(6)/SP(6),* Minimal moose $SU(3)^2/SU(3)$ and general mooses $SU(3)^n/SU(3)^k$, *etc*. They have similar particle content and are less constrained.
- More detailed information on the ATLAS searches can be found in *G. Azuelos et al., hep-ph/0402037*

LITTLE HIGGS SEARCHES AT LHC

on behalf of ATLAS Collaboration

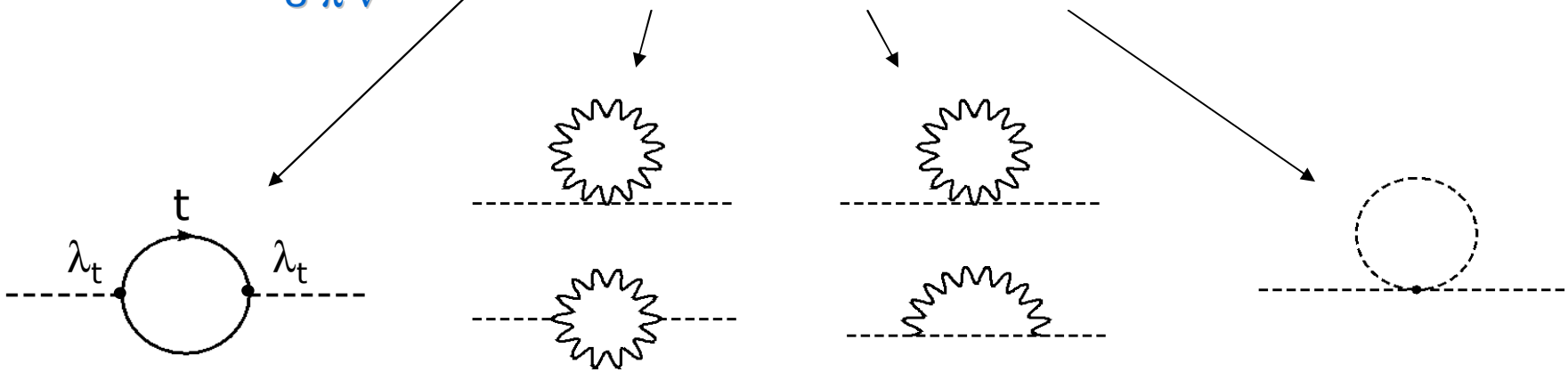
presented by: Jose E. Garcia *(IFIC-Valencia)*

The Littlest Higgs model



Corrections

$$\delta m_h^2 = \frac{3\Lambda^2}{8\pi^2 v^2}\left(4m_t^2 - 2M_w^2 - 4M_z^2 - m_h^2\right)$$



Minimum needed to cancel all loops

T	heavy top	➡	new EW singlet
W_H, Z_H	heavy gauge bosons	➡	new SU(2)⊗U(1) symmetry
Φ	heavy higgs bosons	➡	many new Goldstone bosons EW triplet (ϕ^0 , ϕ^+ , ϕ^{++})

Mass Range

Upper limits:

to avoid fine tuning scale ➡ $f < 1\ \text{TeV} \cdot \left(\frac{m_h}{200\, GeV} \right)^2$

T ⇒ $M < 2\ \text{TeV} \cdot \left(\frac{m_h}{200\, GeV} \right)^2$

$m_h = 120$ GeV	$M < 0.2$ TeV
$m_h = 200$ GeV	$M < 2$ TeV

$W_H^{\pm}$, Z_H, A_H ⇒ $M < 6\ \text{TeV} \cdot \left(\frac{m_h}{200\, GeV} \right)^2$

$m_h = 120$ GeV	$M < 2.2$ TeV
$m_h = 200$ GeV	$M < 6$ TeV

ϕ ⇒ $M < 10$ TeV

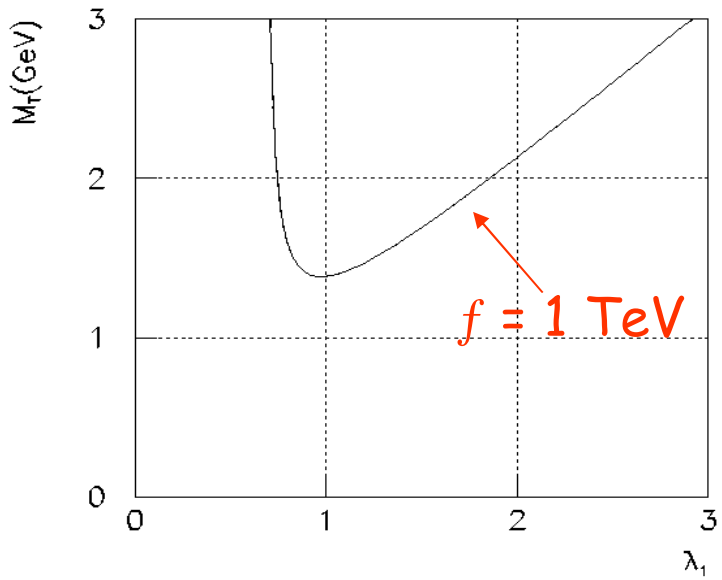
Little Higgs t and χ will mix $\rightarrow$ standard top t, heavy top T

$$M_t \approx \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}\, v + O\left(\frac{v^2}{f^2}\right) \qquad M_T \approx \sqrt{\lambda_1^2 + \lambda_2^2}\, f + O\left(\frac{v^2}{f^2}\right)$$

v = electroweak scale = 244 GeV
f = heavy scale ~ 1 TeV
λ_1, λ_2 = Yukawa couplings O(1)

λ_2 can be eliminated using SM top mass

$\rightarrow$ 2 new free parameters, f, λ_1



$$M_T \approx 1.4 f \frac{\lambda_1}{\sqrt{2.1 - \frac{1}{\lambda_1^2}}}$$

f > 1 TeV
(EW data!)

but if M_T is too large $\rightarrow$ fine tuning

Littlest Higgs: particle content and couplings

new particles	couplings	mass
T	$\lambda_1 \quad \lambda_2$	$M_T = \sqrt{\lambda_1^2 + \lambda_2^2}\, f + O\left(\frac{v^2}{f^2}\right)$
$W_H^{\pm},\ Z_H$	$c = \cos\theta \quad s = \sin\theta$	$M_{Z_H} = M_{W_H} = m_w \left(\frac{f}{v}\right) \frac{1}{sc} + O\left(\frac{v^2}{f^2}\right)$
A_H	$c' = \cos\theta' \quad s' = \sin\theta'$	$M_{A_H} = M_Z \sin^2\theta_W \left(\frac{f}{v}\right) \frac{1}{5s'c'} + O\left(\frac{v^2}{f^2}\right)$
$\phi^0,\ \phi^+,\ \phi^{++}$	$v \quad v'$	$M_\phi^2 = \frac{2m_h^2 f^2}{v^2} \frac{1}{\left[1-(4v'f/v^2)^2\right]}$

New constants: scale f and λ_1, θ, θ', v'

weakness of the model

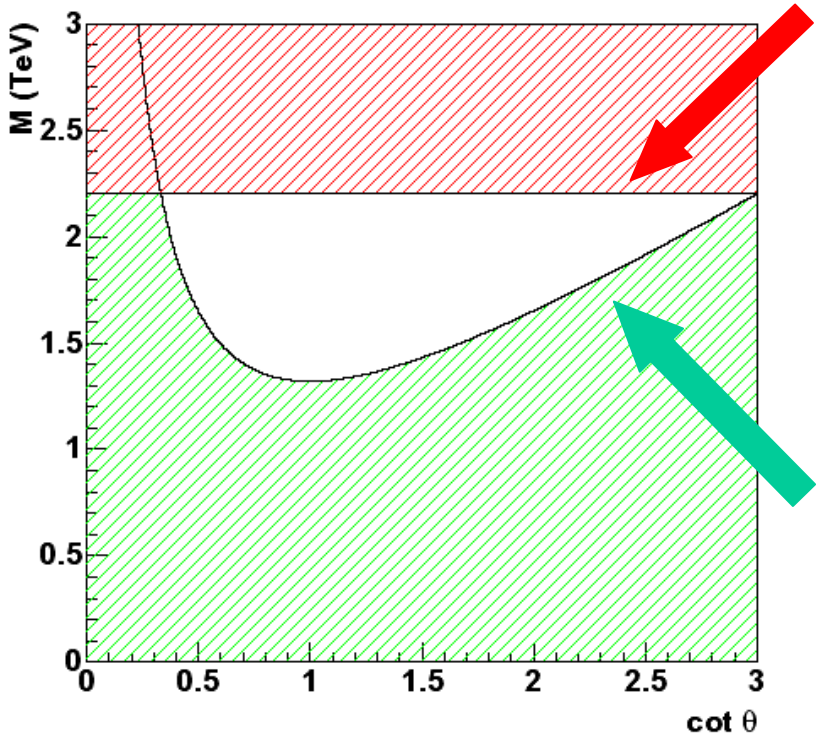
- No relations between these new constants
- A_H couplings not fixed by the model
- EW data $\rightarrow f \leftarrow$ fine tuning

  2 TeV < f < 4 TeV

Expectations for Z_H

$$M(Z_H) \approx m_W\,(f/v)\,[\cot\theta + 1/\cot\theta]$$

f = scale for new physics
v = Fermi scale (244 GeV)



Avoid fine tuning ⇒ M < 2.2 TeV
(assuming m_h = 120 GeV)

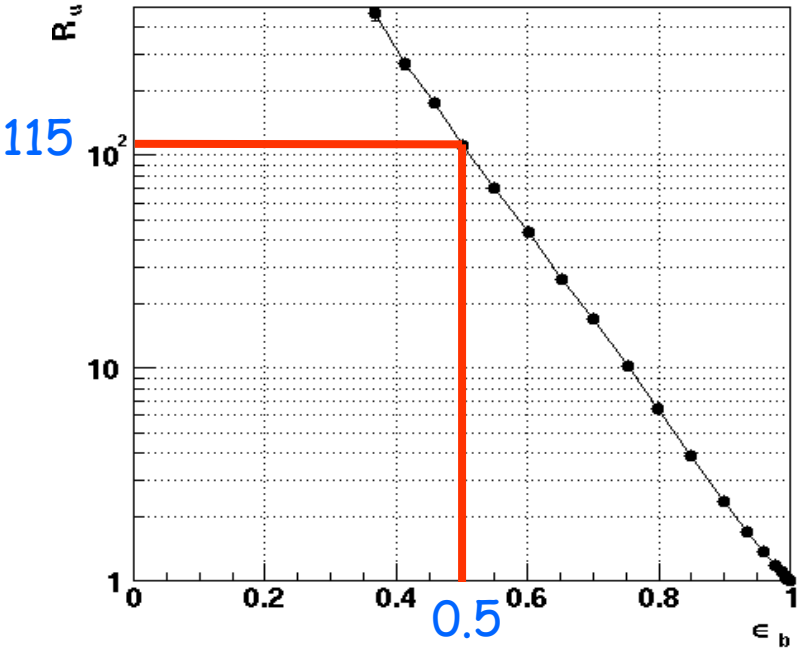
M expected in 1-2 TeV region with wide range of cot θ parameter.

Agree with EW data ⇒ f > 2 TeV

b-tagging

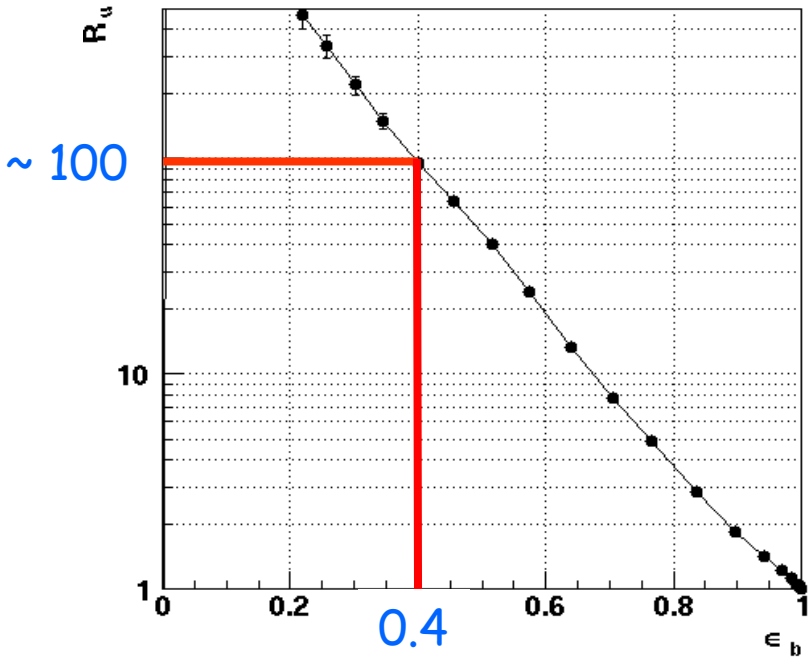
M_{Z_H} = 1 TeV

$< p_T(b) > =$ 220 GeV



M_{Z_H} = 2 TeV

$< p_T(b\bar{b}) > =$ 800 GeV



Little Higgs Model Discrimination at the LHC and ILC

Jürgen Reuter

Albert-Ludwigs-Universität Freiburg

Kilian, JR **PRD 70** (2004), 015004; Kilian, Rainwater, JR **PRD 71** (2005), 015008; **PRD 74** (2006), 095003, and work in progress

SUSY 07, Karlsruhe, July 27th, 2007

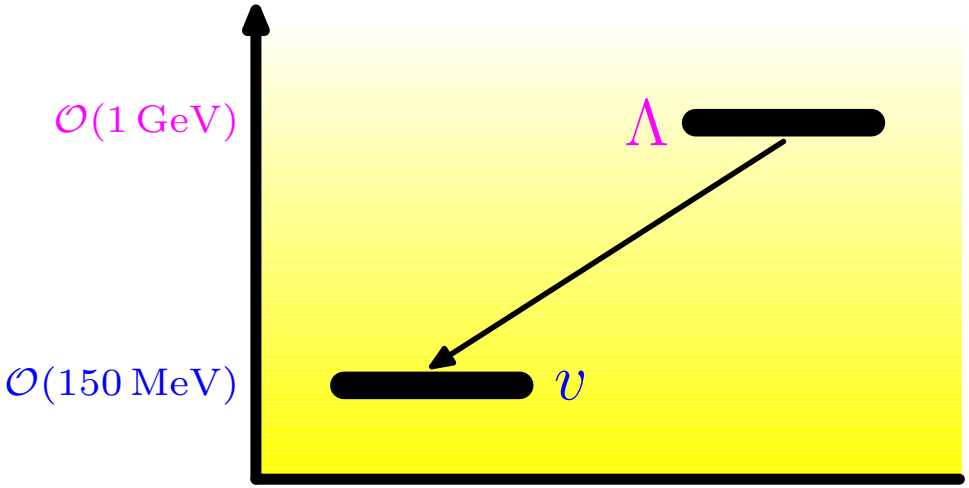
What if not SUSY?

Higgs as Pseudo-Goldstone boson

Nambu-Goldstone theorem: Spontaneous Breaking of a global symmetry: massless (Goldstone) bosons in the spectrum

Old idea: Georgi/Pais, 1974; Georgi/Dimopoulos/Kaplan, 1984

Light Higgs as (Pseudo)-Goldstone boson of a spontaneously broken global symmetry



Analogous: QCD

Scale Λ: chiral symmetry breaking, quarks, $SU(3)_c$

Scale v: pions, kaons, ...

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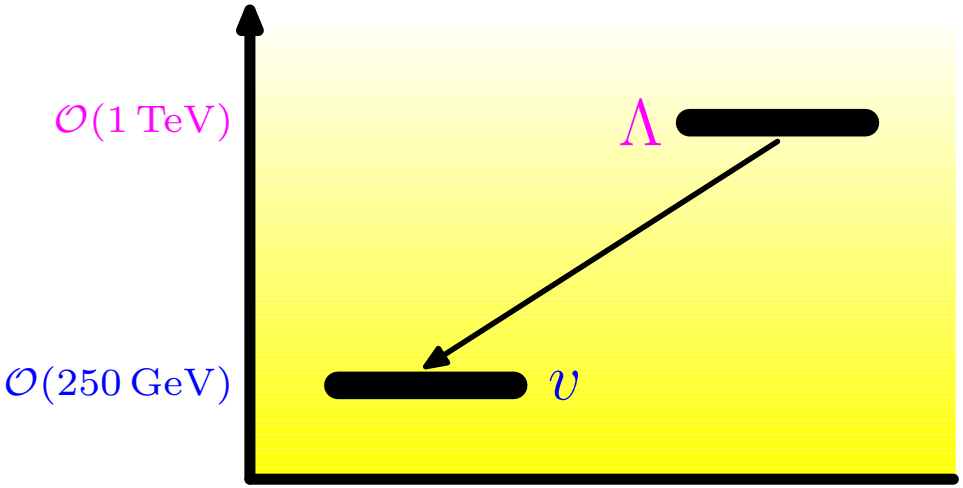


Scale Λ: global symmetry breaking, new particles, new (gauge) IA

Scale v: Higgs, W/Z, $\ell^{\pm}$, ...

Without Fine-Tuning: experimentally excluded

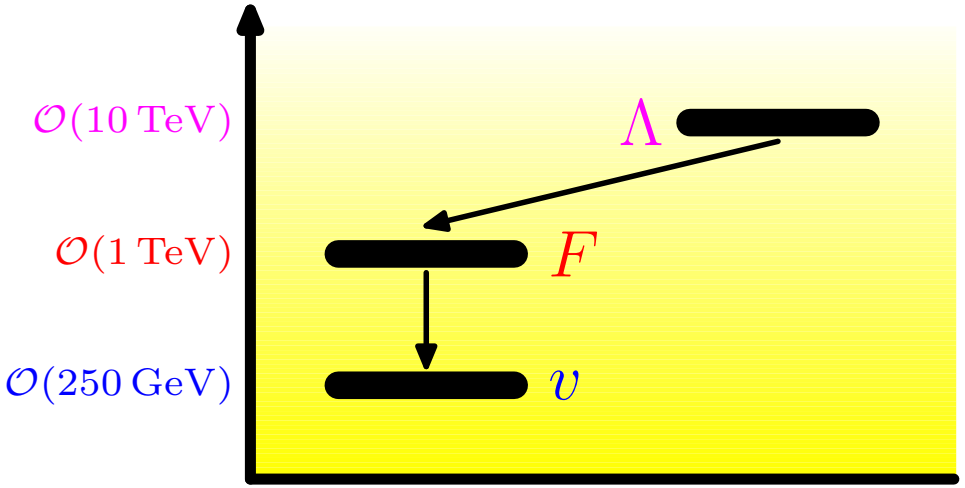
Collective symmetry breaking and 3-scale models

Collective symmetry breaking: Arkani-Hamed/Cohen/Georgi/Nelson/..., 2001

2 different global symmetries; one of them unbroken $\Rightarrow$ Higgs *exact* Goldstone boson

Coleman-Weinberg: boson masses by radiative corrections, but: m_H only at 2-loop level

$$m_H \sim \frac{g_1}{4\pi}\frac{g_2}{4\pi}\Lambda$$



Scale Λ: global SB, new IA

Scale F: Pseudo-Goldstone bosons, new vectors/fermions

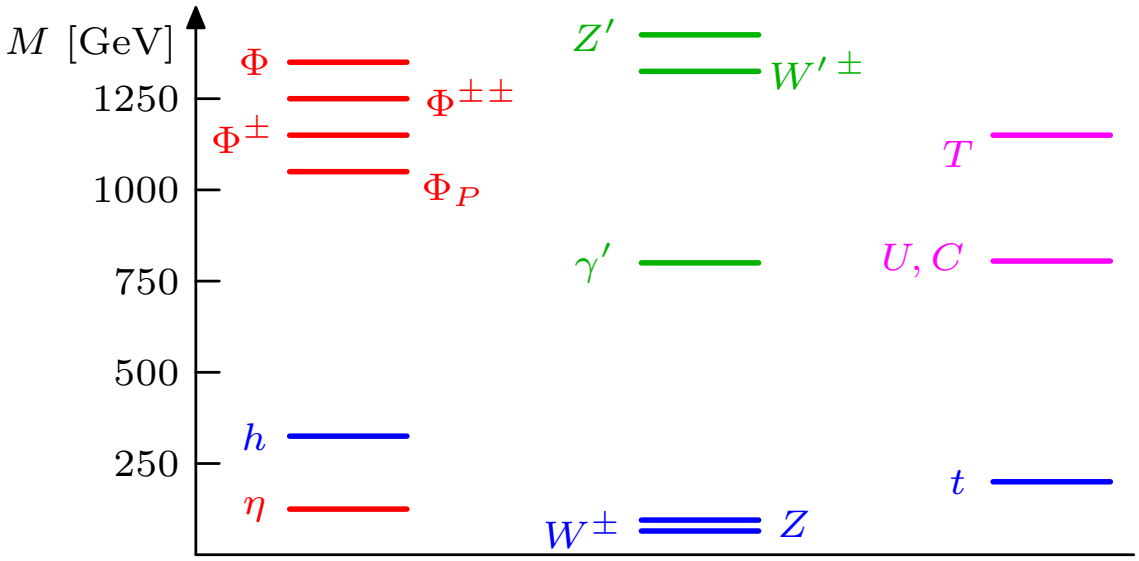
Scale v: Higgs, W/Z, $\ell^\pm$, ...

Properties of Little-Higgs models

- Extended global symmetry
- Specific functional form of the potential
- Extended gauge symmetry:
  $\gamma', Z', W'^{\pm}$
- New heavy fermions: T, but also $U, C, \ldots$

Example: Littlest Higgs

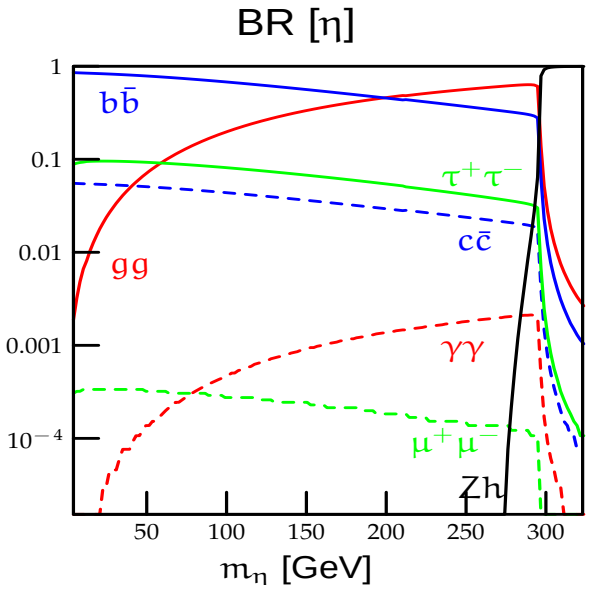
Arkani-Hamed/Cohen/Katz/Nelson, 2002



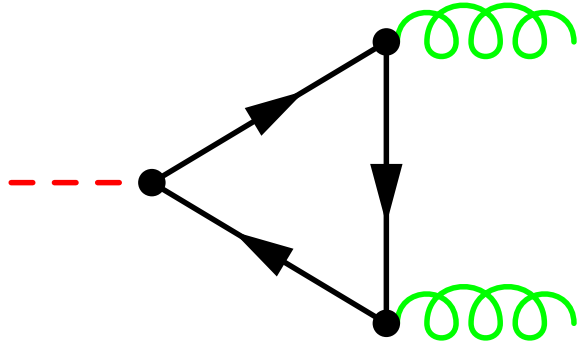
Pseudo-Axions in Little Higgs

Kilian/Rainwater/JR, 2004, 2006; JR, 2007

- gauged $U(1)$ group: $Z' \longleftrightarrow$ ungauged: η
- couples to fermions like a pseudoscalar
- $m_\eta \lesssim 400\,\text{GeV}$
- SM singlet, couplings to SM particles v/F suppressed
- η axion-like particle:



Anomalous $U(1)$:



$$\longrightarrow \frac{1}{F}\frac{\alpha_s}{8\pi^2}\eta F_{\mu\nu}F_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$

- $U(1)$ explicitly broken $\Rightarrow$ Axion limits from astroparticle physics not applicable

Classification of Axions in Little Higgs Models

Number of Pseudo-Axions: $n = g - l$
Mismatch between global (g) and local rank reduction (l)

Product Group Models

Arkani-Hamed,...

- Doubling of electroweak gauge group: $SU(2) \times SU(2) \to SU(2)_L$, $U(1) \times U(1) \to U(1)_Y$ (latter not necessary) $\Rightarrow l = 1$
  - Littlest Higgs, g: $SU(5) \to SO(5) \Rightarrow n = (4-2) - 1 = 1$
  - antisymmetric, g: $Sp(6)/SO(6)$, $n = (3-2) - 1 = 0$

Simple Group Models

Kaplan,Schmaltz, ...

- Simple gauge group: $SU(N) \times U(1) \to SU(2) \times U(1) \Rightarrow \; l = N - 2$
- Higgs is distributed over several global symmetry multiplets
- Simplest Little Higgs, g: $[SU(3)]^2/[SU(2)]^2$ $\quad n = g - l = 2 - 1 = 1$
- Original Simple Group Model, g: $[SU(4)]^3/[SU(3)^3 \times SU(2)]$, l: $SU(4) \to SU(2)$ $\quad n = g - l = 4 - 2 = 2$

Moose Models

Arkani-Hamed, ...

- "Minimal" Moose: g $[SU(3)]^4 \to SU(3)$, l $[SU(3) \times SU(2)]/SU(2)$ $n = g - l = 6 - 2 = 4$
- 3-site model: g $[SU(2)]^4/[SU(2)]^2$, l $[SU(2)]^2 \to SU(2)$, $n = 2 - 1 = 1$

$ZH\eta$ coupling as a discriminator

Kilian/Rainwater/JR, 2006

- pseudo-axion: $\xi = \exp[i\eta/F]$, $\Sigma = \exp[i\Pi/F]$ non-linear representation of the remaining Goldstone multiplet Π

$$\mathcal{L}_{\text{kin.}} \sim F^2 \,\text{Tr}\left[(D^\mu(\xi\Sigma)^\dagger(D_\mu(\xi\Sigma))\right] = \ldots - 2F(\partial_\mu\eta)\,\text{Im}\,\text{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] + O(\eta^2)$$

- Use special structure of covariant derivatives:

$$D_\mu\Sigma = \partial_\mu\Sigma + A^a_{1,\mu}\left(T^a_1\Sigma + \Sigma(T^a_1)^T\right) + A^a_{2,\mu}\left(T^a_2\Sigma + \Sigma(T^a_2)^T\right),$$

$$\text{Tr}\left[(D^\mu\Sigma)^\dagger\Sigma\right] \sim W^a_\mu \,\text{Tr}\left[\Sigma^\dagger(T^a_1 + T^a_2)\Sigma + (T^a_1 + T^a_2)^*\right] = 0.$$

- Little Higgs mechanism cancels this coupling
- Simple Group Models: $\Phi = \exp[i\Sigma/F]$, $\zeta = (0, \ldots 0, F)^T$ VEV directing in the N direction

$$\mathcal{L}_{\text{kin.}} \sim F^2 D^\mu(\zeta^\dagger\Phi^\dagger)D_\mu(\Phi\zeta) = \ldots + \frac{i}{F}(\partial_\mu\eta)\zeta^\dagger\left(\Phi^\dagger(D_\mu\Phi) - (D_\mu\Phi^\dagger)\Phi\right)\zeta$$
$$= \ldots + iF(\partial_\mu\eta)\left(\Phi^\dagger(D_\mu\Phi) - (D_\mu\Phi^\dagger)\Phi\right)_{N,N} .$$

$$\Sigma = \begin{pmatrix} 0 & h \\ h^\dagger & 0 \end{pmatrix}, \qquad \mathbb{V}_\mu = \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \text{heavy vector fields}$$

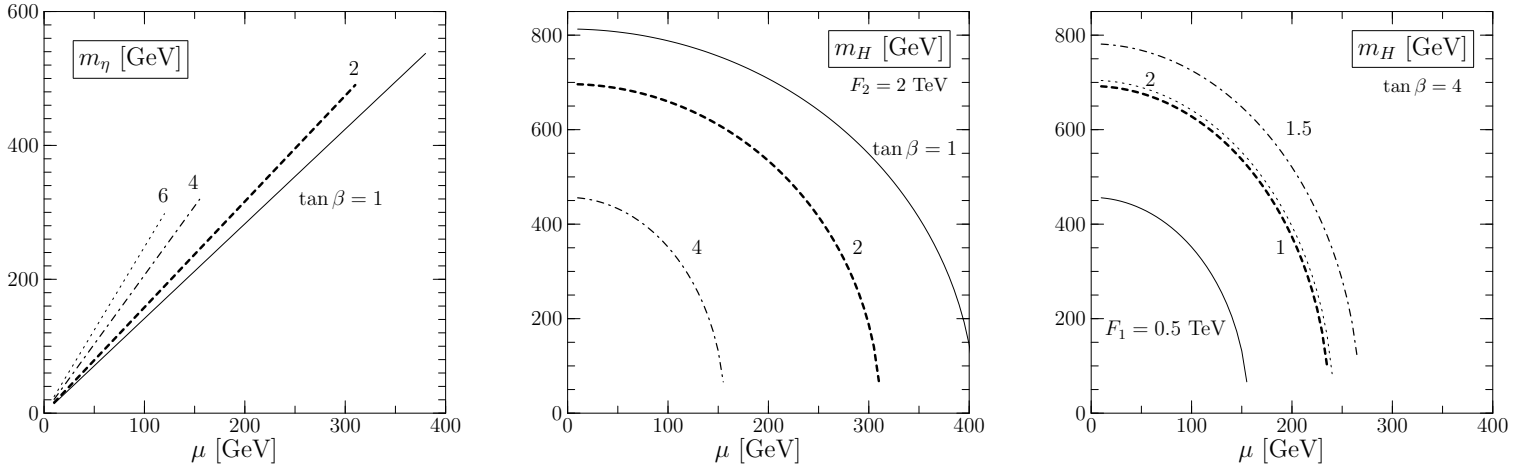
$$\mathbb{V}_\mu + \frac{i}{F}[\Sigma, \mathbb{V}_\mu] - \frac{1}{2F^2}[\Sigma, [\Sigma, \mathbb{V}_\mu]] + \ldots$$
$$= \begin{pmatrix} \mathbb{W}_\mu & 0 \\ 0 & 0 \end{pmatrix} + \frac{i}{F}\begin{pmatrix} 0 & -\mathbb{W}_\mu h \\ h^\dagger\mathbb{W}_\mu & 0 \end{pmatrix} - \frac{1}{2F^2}\begin{pmatrix} hh^\dagger\mathbb{W} + \mathbb{W}hh^\dagger & 0 \\ 0 & -2h^\dagger\mathbb{W}h \end{pmatrix} + \ldots$$

- 1st term cancels by multiple Goldstone multiplets
- 2st term cancels by EW symmetry
- 3rd term

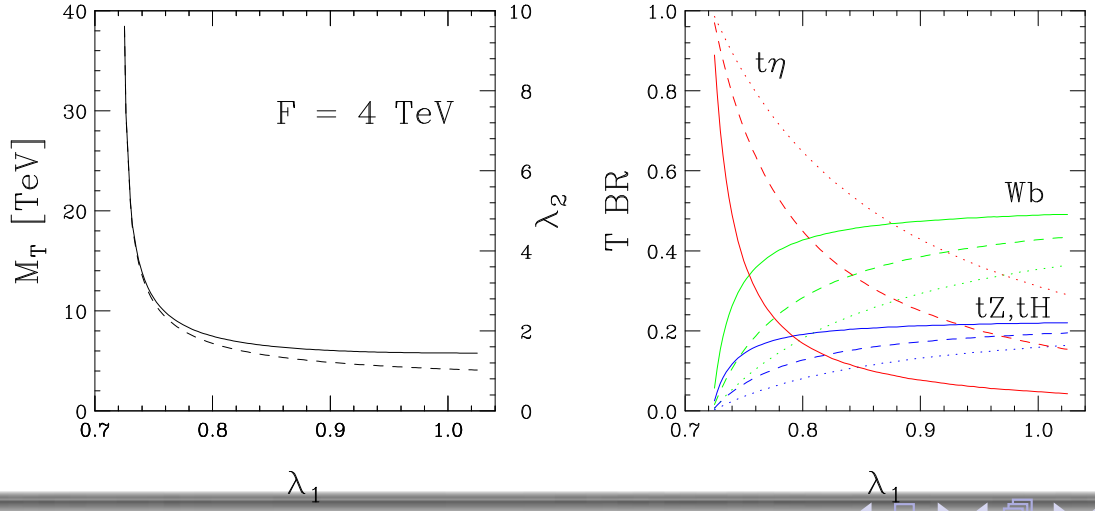
$$(\partial^\mu\eta)h^\dagger\mathbb{W}_\mu h \sim vHZ_\mu\partial^\mu\eta .$$

More properties of Pseudo-Axions

- Take e.g. one specific model: Simplest Little Higgs Schmaltz, JHEP **0408** (2004) 056
- Simple Group Model, two Higgs-triplets with a $\tan\beta$-like mixing angle



- $\tan\beta \sim 1$: heavy Higgs, (very) light pseudoscalar
- Heavy top decays: Kilian/Rainwater/JR, 2006



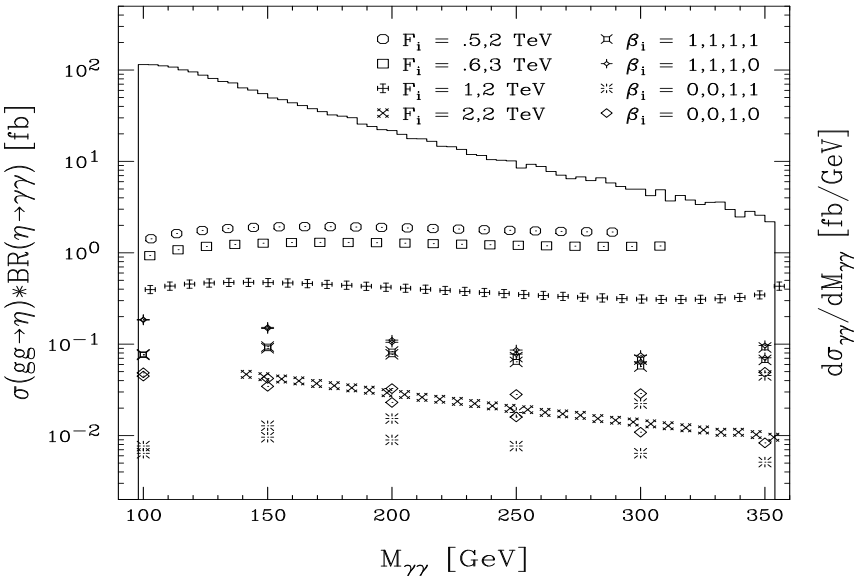
Discovery of Pseudo-axions

Kilian/Rainwater/JR, 2004, 2006

LHC: Gluon fusion, diphoton signal for $m_\eta \gtrsim 200\,\text{GeV}$, 7σ possible

LHC: $T \to t\eta$

ILC: $e^+e^- \to t\bar{t}\eta$



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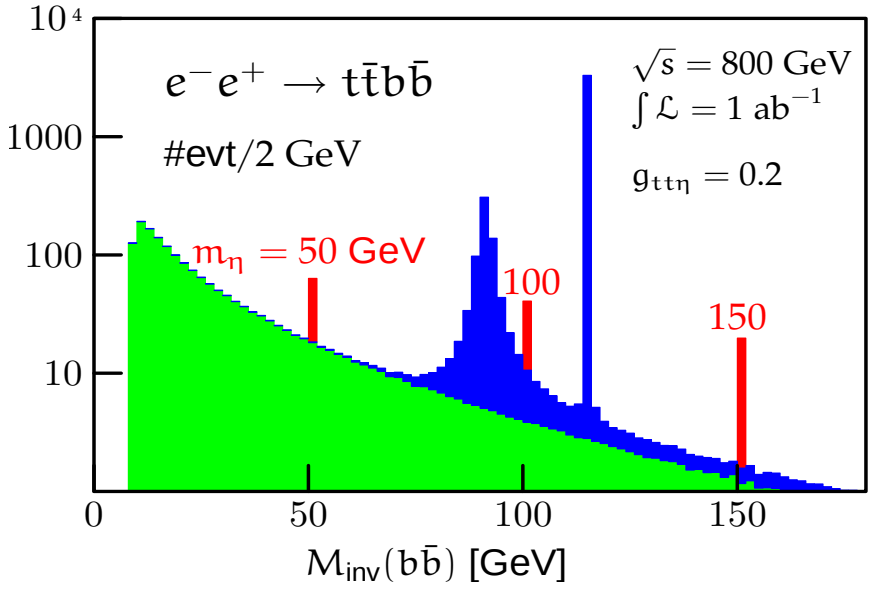

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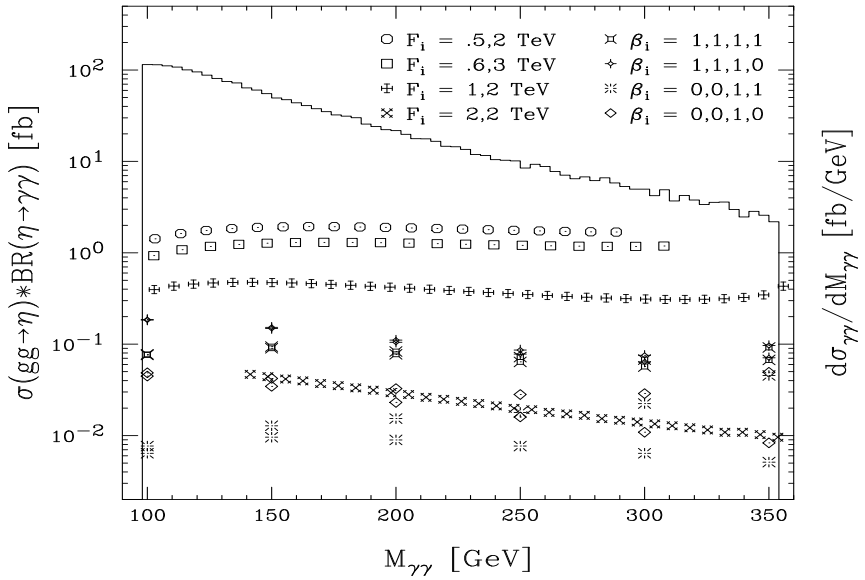

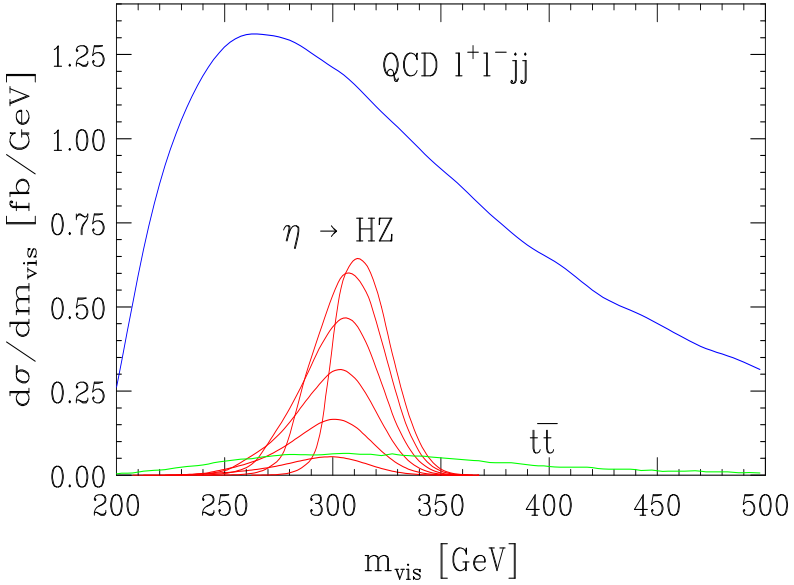

$ZH\eta$ coupling

forbidden in Product Group Models

Discriminator of diff. model classes

$$gg \to \left\{ \begin{array}{ll} H \to Z\eta & \to \ell\ell bb \\ \eta \to ZH & \to \ell\ell bb, \ell\ell\ell jj \end{array} \right\}$$

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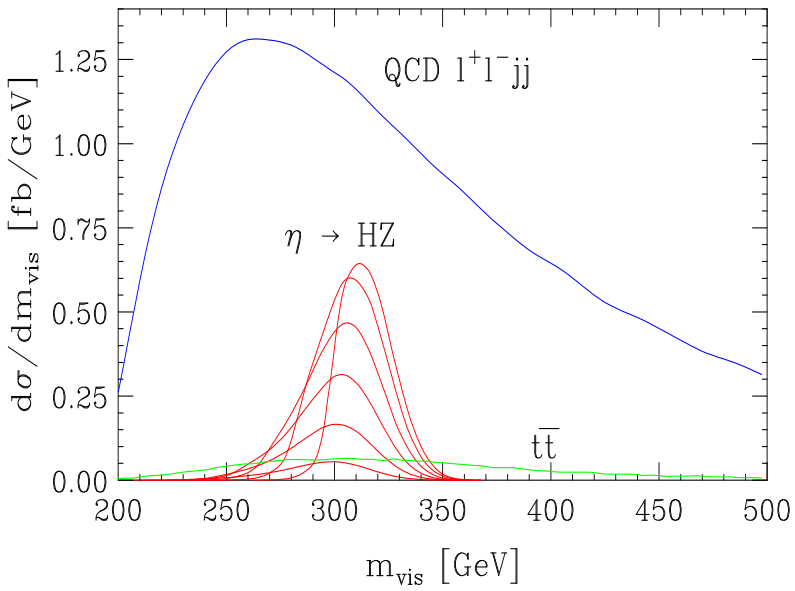

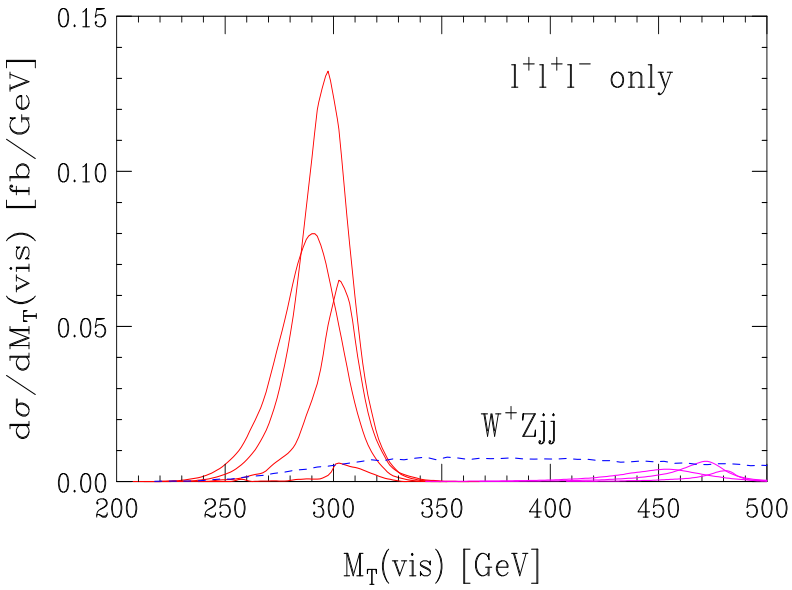

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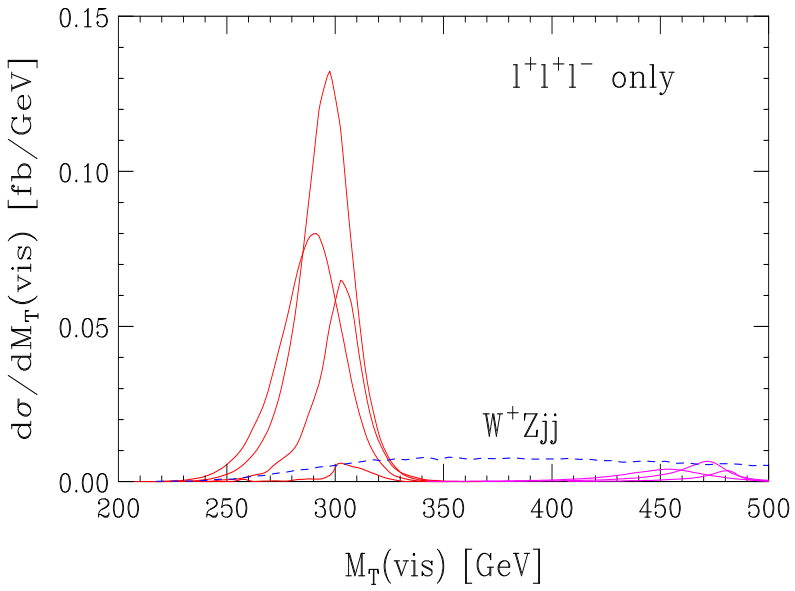

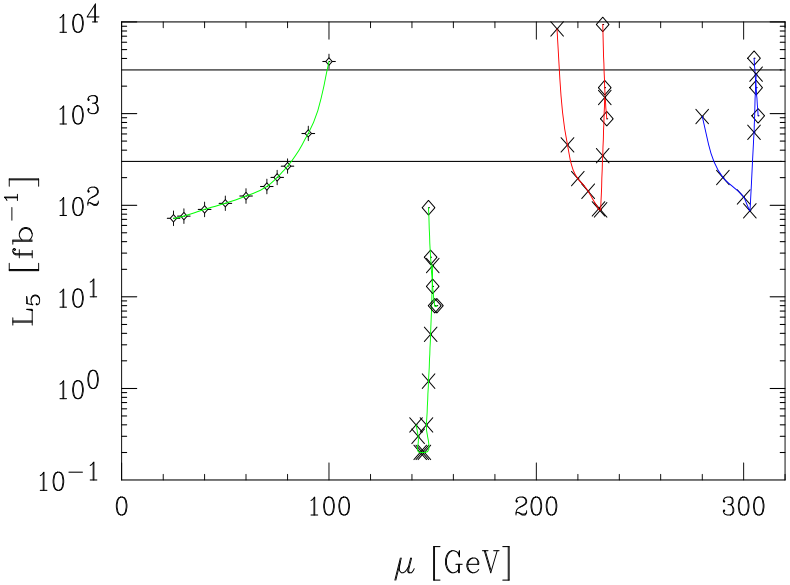

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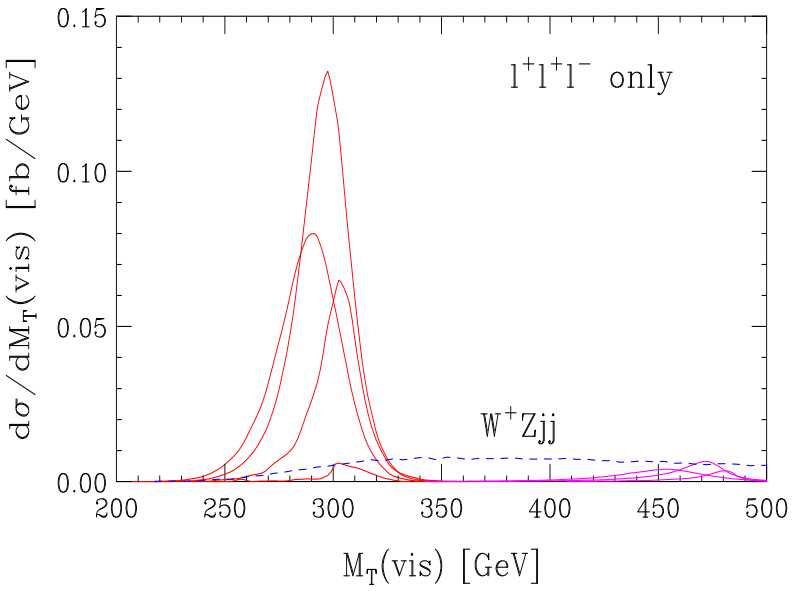

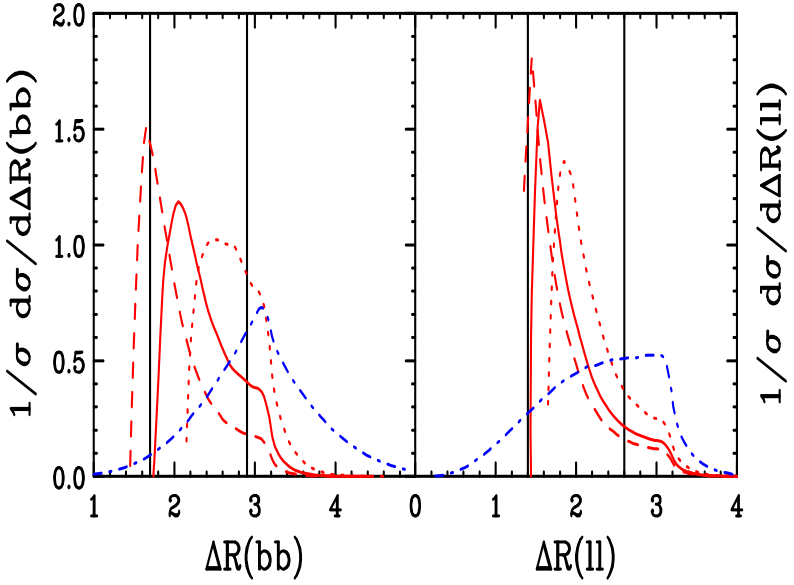

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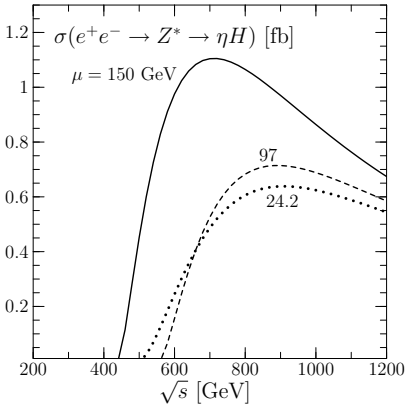
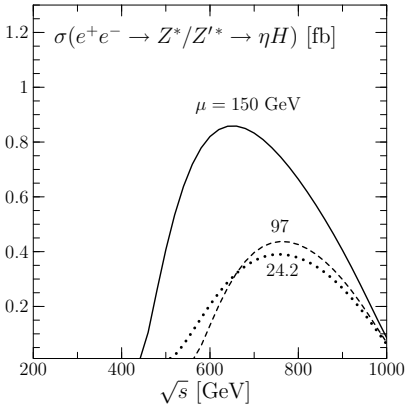
η pheno at ILC

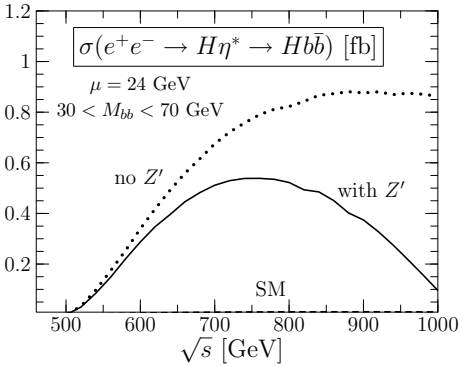
Kilian/Rainwater/JR, 2006

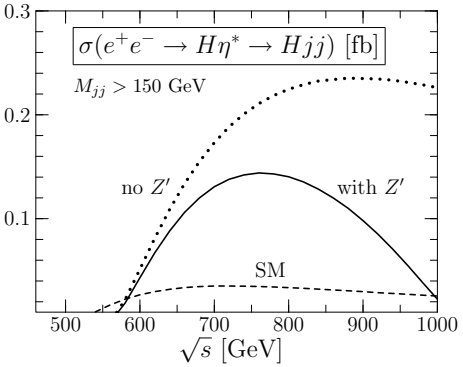
If $ZH\eta$ coupling present: $H\eta$ production in analogy to HA:

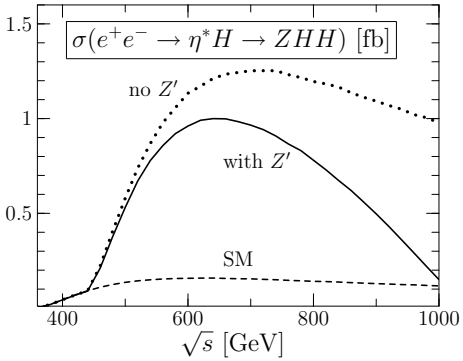




- Light pseudoaxion, $\eta \to bb$, final state Hbb
- Intermediate range, $\eta \to gg$, final state Hjj
- $\eta \to ZH$: ZHH final state







More detailed insights from photon collider option

η pheno at ILC

Kilian/Rainwater/JR, 2006

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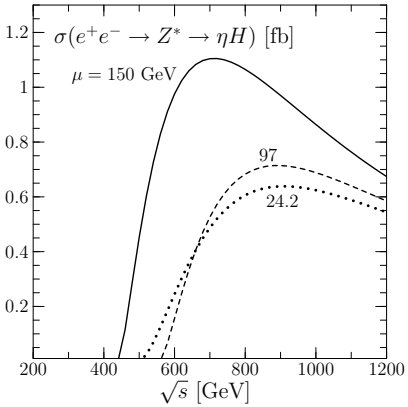

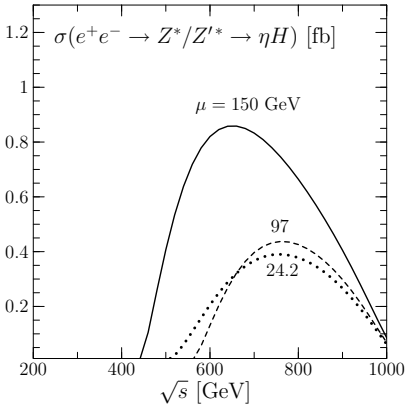

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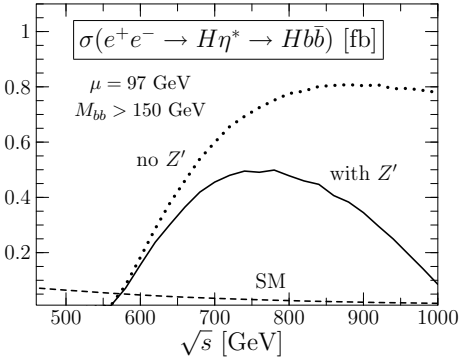
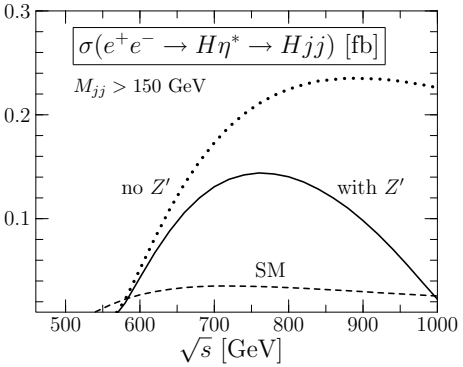
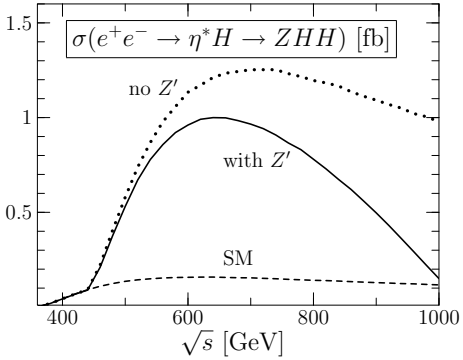
- $\eta \to ZH$: ZHH final state







More detailed insights from photon collider option

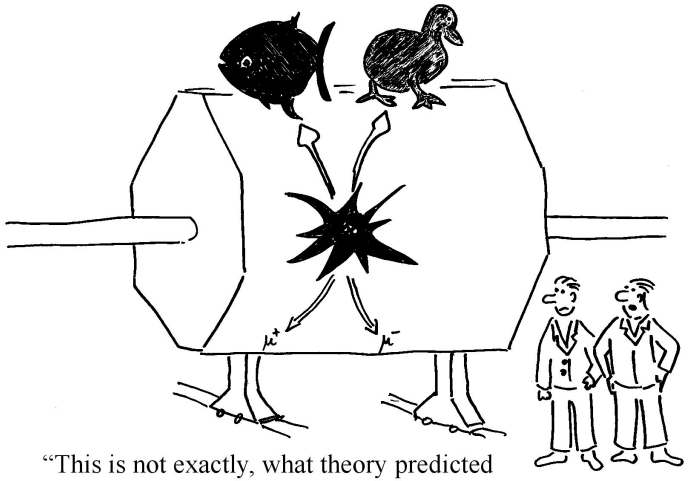
Invisible Higgs decays (?)

- "Invisible decay" $H \to \eta\eta$ [quite similar to $H \to aa$ in NMSSM]
  but only due to mixing effects because
  $U(1)_\eta$ protective symmetry

$$\Gamma_{H\to\eta\eta} \sim \frac{1}{16\pi}\sqrt{1-\frac{4m_\eta^2}{m_H^2}}\frac{v^5}{F^4} \sim \frac{15}{(F\,[\text{TeV}])^4}\ \text{MeV}$$

- Light Higgs might become invisible at the LHC $H \to \eta\eta \to jjjj$
  - Not possible in Simplest Little Higgs
  - Possible in other Simple Group Models (together with η, A mixing)
  - Can become the dominant decay (with BR $\sim .8 - .95$)
- ILC can cover that hole!

JR, 2007



"This is not exactly, what theory predicted for the Higgs decay!"

Summary

- Higgs is generically heavy in LHM; will be captured by VV mode
- Little Higgs models generally have extra pseudoscalars
- Pseudo-Axions *not ruled out* by astro-limits
- Discriminator between Product and Simple Group Models: $ZH\eta$, $Z'H\eta$ coupling
- LHC has first option:
  - $gg \to H \to Z\eta$ (only on-shell)
  - $gg \to \eta \to ZH$ (only on-shell)
  - $Z' \to Z\eta$ $W' \to W\eta$ $T \to t\eta$
- Cross references from heavy quark and Z', W' discoveries
- ILC is sensitive in all parameter regions
- Possible degeneracies between Higgs/pseudoaxion ($\gamma\gamma$ option)
- Importance of “invisible” decays?